The northern Caribbean plate boundary in the Jamaica Passage: structure and seismic stratigraphy

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1. Introduction

The deadly Mw 7.0 Haiti earthquake of 2010 reminded us of the necessity to characterize the structures and improve understanding of the tectonic processes acting along the northern Caribbean plate boundary. This plate boundary extends from Central America to Puerto Rico and is defined mainly by offshore strike-slip faults, including the Swan Fault, the Septentrional-Oriente Fault Zone (SOFZ), the Walton Fault and the Enriquillo-Plantain-Garden Fault Zone (EPGFZ; Fig. 1). Although previous seismic reflection data acquisition has led to a description of the seismic stratigraphy of the eastern Cayman Trough and the northeastern Lower Nicaraguan Rise (Fig. 1; Leroy *et al.*, 1996; Mauffret and Leroy, 1997; Mauffret and Leroy, 1999), our knowledge of the tectonics remains sparse along several segments of the Northern Caribbean plate boundary. For example, our knowledge of the Jamaica Passage between Jamaica and Hispaniola, which is crossed by the EPGFZ, was formerly based on widely-spaced and low resolution seismic reflection profiles and bathymetry (Robinson and Cambray, 1971; Horsfield and Robinson, 1974; Case and Holcombe, 1980; Mann *et al.*, 1995). During November-December 2012, a marine geophysical survey (HAITI-SIS) was carried out aboard the Research Vessel *L'Atalante* around the northern Caribbean plate boundary to unravel the detailed geometry of the active fault system (Leroy *et al.*, 2015).

Our study focuses on the Jamaica Passage, with the aim of deciphering and characterizing its structure and stratigraphy (Fig. 1). We use high-resolution multibeam bathymetry and 60 multi-channel seismic reflection profiles to image the EPGFZ and the crustal domains between Jamaica and Hispaniola. The bathymetric map highlights the recent fault trace of the EPGFZ as well as distinct morphological features. The seismic reflection profiles acquired during the HAITI-SIS cruise are compared with former reflection seismic studies in the Caribbean area in order to define the main stratigraphic sequences in the Jamaica Passage. Based on morphological, structural and sedimentological criteria derived from the combined interpretation of the bathymetry and seismic data, we identify two distinct crustal domains and two distinct basin structures in the vicinity of the EPGFZ. The new HAITI-SIS data set is then used to propose a structural sketch of the Jamaica Passage and highlights its main tectonic features.

2. Geological setting

The Caribbean plate's interior is mainly formed by a Cretaceous Oceanic Plateau, known as the Caribbean Large Igneous Province (CLIP). This province is covered by extended lava flows of varying thickness that cover an igneous basement. Seismic stratigraphy studies of the Caribbean crust have described several seismic units typical of oceanic material in the Colombian Basin (Lu and McMillen, 1982; Bowland, 1993) and in the Venezuelan Basin (Ladd and Watkins, 1980; Ladd *et al.*, 1990; Diebold *et al.*, 1999; Driscoll and Diebold, 1999) with thickness of the crust around 5 km. Moreover, the interpretation of seismic reflection data has led to identification of the Carib Beds (Caribbean typical prominent reflection horizons A" and B"), which have been drilled and widely mapped in the Venezuelan Basin (Fig. 1; Ladd and Watkins, 1980; Diebold *et al.* 1981; Diebold *et al.*, 1999; Driscoll and Diebold, 1999; Granja Bruña *et al.*, 2009; Kroehler *et al.*, 2011), in the southwest and west of the Colombian Basin (Fig. 1; Bowland, 1993; Bowland and Rosencrantz, 1988), south of the Beata Ridge (Fig. 1; Hopkins, 1973; Stoffa *et al.*, 1981) and in the Lower Nicaraguan Rise (Fig. 1; Mauffret and Leroy, 1997).

The CLIP was formed during the Cretaceous on the Pacific Farallon plate, over the Galapagos hotspot (Duncan and Hargraves, 1984), while the Greater Antilles volcanic arc (*i.e.*, Cuba, Hispaniola and Puerto Rico) was initiated by an eastward dipping subduction in Central America (Pindell, 2012; Van der Lelij, 2013; Hastie *et al.*, 2013). The volcanic arc and the plateau subsequently moved north- and eastwards to their current position between the North and South American plates, thus individualizing the current Caribbean plate. The eastern Greater Antilles arc (*i.e.*, Hispaniola and Puerto

Rico) became an inactive intra-oceanic arc during the northeastward motion of the Caribbean plate. The northeastward motion of the newly formed Caribbean plate lasted until the beginning of the collision between the western Cuban arc and the Bahamas carbonate platform in the Paleocene (Leroy *et al.*, 2000, Cruz-Orosa *et al.*, 2012).

The progressive collision between the Cuban arc and the Bahamas platform led to the localization of a left-lateral fault zone south of Cuba, followed by the opening of the Cayman Trough system during the Eocene (Fig. 1; Mann, 1997; Leroy *et al.* 2000; Pubellier *et al.*, 2000). The Cayman Trough (CT in Fig. 1) is a narrow oceanic trough created on either side of a short spreading centre (MCSC, Mid-Cayman Spreading Centre) separating the conjugate passive margins of Belize in the West and North Jamaica in the East, as a response to the northeastward motion of the Caribbean plate relative to the North American plate (Holcombe *et al.*, 1973; Goreau, 1981; Rosencrantz and Sclater, 1986; Rosencrantz *et al*., 1988; Leroy *et al.*, 1996).

Studies including multichannel seismic acquisition (Sykes *et al.*, 1982; Leroy *et al.*, 1996) and swath mapping (Rosencrantz and Mann, 1991; Leroy *et al.*, 1996) in the eastern Cayman Trough, as well as field mapping in Jamaica (Burke *et al.*, 1980; Abbott *et al.*, 2013, James-Williamson *et al.*, 2014) were carried out to understand the opening of the Cayman Trough system since the early Eocene and the formation of the North Jamaica passive margin. Leroy *et al.* (1996) interpreted the basement of the eastern Cayman Trough, between Cuba and Jamaica, as a Mesozoic continental crust rifted in a succession of parallel tilted blocks trending northeast-southwest (Fig. 2). These blocks form a series of sedimentary basins initiated and infilled during the rifting phase. The onset of oceanic spreading at the toe of the margin (Fig. 2) is dated at about 49 Ma by the record of magnetic anomaly 22 (Ypresian, early Eocene; Leroy *et al.*, 2000; Hayman *et al.*, 2011) in agreement with onshore studies, contrary to Rosencrantz *et al.* (1988) dating the opening at anomaly 20 (~40 Ma). At a first-order level, the transition from rifting to oceanic spreading corresponds to an unconformity separating the tilted syn-rift seismic sequences from the post-rift layers on the proximal margin domain. Unfortunately, there are no drill-holes to constrain the age of the sediments infilling the basins. However, owing to the exposure of such a basin subsequently inverted as a restraining bend in Jamaica, the ages of the syn-rift seismic sequence can be estimated by comparison with their onshore equivalents. The Wagwater inverted graben (Fig. 2) is filled by syn-rift Paleocene and early Eocene sediments (Richmond and Wagwater formations; Mann, 1985; Mann and Burke, 1990), representing the equivalent of the extensional regime of the eastern passive margin of the Cayman Trough system during the rifting time. The associated normal faults of the Blue Mountains (BM; Fig. 2) were then sealed by an accumulation of carbonate formations (Yellow Limestone and White Limestone) associated with post-rift platforms, from the middle Eocene to the middle Miocene (Wadge and Dixon, 1984). This time-span of rifting fits well with that observed on the eastern Cayman Trough margin (Leroy *et al.*, 1996; 2000).

During the early Miocene (ca. 20 Ma), a major sedimentary unconformity is recorded in southeastern Cuba and on Hispaniola (Bowin, 1975; Calais and Mercier de Lépinay, 1995; Dillon *et al.*, 1992). This unconformity relates to a paleogeographic rearrangement, induced by the obliquity of the convergence between Cuba and Hispaniola to the south and the Bahamas to the North (Pindell and Barrett, 1990; Mann *et al.*, 1995). At the same time, Cuba and Hispaniola begin to be separated along the SOFZ (Fig. 1; Pindell and Barrett, 1990). Moreover, during the Miocene, the CLIP collides with the southwest of Hispaniola (Calmus, 1983; Pindell and Barrett, 1990; Granja Bruña *et al.*, 2014) and a compressive deformation begins to develop in Hispaniola (Haitian fold-and-thrust belt, Pubellier *et al.*, 2000). The pre-existing structures of Jamaica are overprinted by left-lateral transcurrent tectonics from the middle Miocene onwards (Mann *et al.*, 1985; Lewis and Draper, 1990; James-Williamson *et al.*, 2014). This transcurrent tectonic style is due to the propagation of the southeastern edge of the Cayman Trough along the offshore Walton fault west of Jamaica and along the EPGFZ in Jamaica, extending to onland Hispaniola as well as into the Jamaica Passage between Jamaica and Hispaniola (Fig. 2; Mann *et al.*, 1995; Leroy *et al.*, 2000).

Currently, the eastward motion of the Caribbean plate is still accommodated along the major transform faults that extend from Central America to Puerto Rico, including the Swan Fault, the SOFZ, the Walton Fault and the EPGFZ (Fig. 1; Mann *et al.*, 2002). The SOFZ to the north and the Walton/EPGFZ to the south are the limits of a crustal block named the Gonâve microplate (Fig. 1; Rosencrantz and Mann, 1991).

3. Previous studies

3.1. Seismic stratigraphy

In the Caribbean realm, the volcanic and rifting events identified in the CLIP and on the North Jamaica passive margin determine distinct kinds of typical seismic stratigraphy as illustrated by the example of the seismic profiles CAS-J02 and CAS-A03 (Fig. 3).

The seismic stratigraphy of the Venezuelan Basin, the Colombian Basin and the Lower Nicaraguan Rise was defined by Ladd and Watkins (1980), Leroy and Mauffret (1996) and Mauffret and Leroy (1997) according to DSDP results (Bader *et al.*, 1970; Edgar *et al.*, 1973). These studies demonstrated that the CLIP forms the substratum defined by four seismic units based on the identification of the typical Caribbean reflection horizons A" and B" as well as reflectors eM and V (Fig. 3B). The upper seismic unit corresponds to early Miocene to Recent chalk marl ooze and clay. The base of this unit is referred to as horizon eM. The second seismic unit that have been drilled corresponds to middle Eocene to lower Miocene radiolarian chalk, and its base is referred to horizon A". The third seismic unit corresponds to lithified chalks, cherts, limestones and black shales. The base of this unit is composed of Santonian to Coniacian basalts named as horizon B". Underneath the third seismic unit, horizons denoted as V, or “Upper volcanic sequence”, correspond to volcanic sills (Diebold *et al.*, 1999). Near the Jamaica Passage, the CLIP was identified in Hispaniola and Jamaica thanks to outcrops (Hastie *et al.*, 2008), in the Lower Nicaraguan Rise thanks to reflection seismic profiles and DSDP and ODP drills (Edgar *et al.*, 1973; Mauffret and Leroy, 1997), and in the Beata Ridge thanks to diving (Mauffret *et al*., 2001) (Figs. 1 and 3). The extent of the identified CLIP is shown in green in Fig. 3.

The structure of the continental passive margin of the eastern Cayman Trough between Cuba and Jamaica was identified by a multichannel seismic survey (Leroy *et al.*, 1996; Fig. 3). The major normal faults bound 10-20 km wide half-grabens displaying escarpments ranging from a few hundred of meters to more than 3 000 m (about 2 s two-way travel time, hereafter referred as twtt). In the NE-SW trending basins, the syn-rift layers are up to 0.2 s twtt thick (~200 m with a velocity in the syn-rift sediments of 2000 m/s) and the post-rift layers are up to 1.2 s twtt thick (~1000 m with a velocity of 1700 m/s). Seismic interpretations based on comparisons with onshore formations in Jamaica identified three main seismic units (Fig. 3a). A lower seismic unit corresponds to faulted and tilted blocks, with internal smooth reflectors consisting of Upper Cretaceous pre-rift sediments. The second seismic unit corresponds to Paleocene to Early Eocene fan-shaped sedimentary bodies, associated with the syn-rift sequence. The upper seismic unit is made up of strong parallel reflectors corresponding to Middle Eocene to Recent deposits related to the post-rift sequence. The extent of the eastern Cayman Trough passive margin identified by Leroy et al. (1996) is shown in blue in Fig. 3.

3.2 Seismic reflection study in the Jamaica Passage

Using four multichannel seismic profiles acquired in 1980 by University of Texas-Institute for Geophysics aboard the R/V Fred Moore, Mann *et al.* (1995) mapped the EPGFZ trace and the main morphological features of the Jamaica Passage (Fig. 4). They imaged a narrow 3-7- km-wide fault trough (the Navassa Basin in this study, Fig. 5) and marked escarpments they used to locate the EPGFZ. They also interpreted the central fault trough as a pull-apart basin cut by faults along both its northern and southern edges. However, the resolution of the seismic reflection lines did not allow them to detail the stratigraphy of the area and to identify the nature of the crustal domains.

4. Data collection

This study makes use of high-resolution multibeam bathymetry and multi-channel seismic reflection data collected during the 2012 HAITI-SIS cruise off Haiti on the R/V *l'Atalante*. The seismic data acquisition was carried out by a 24-channel high-resolution system operated at approximately 9.7 knots (rapid seismic system), with a source composed of two GI guns (shot interval of 10 s) of 2.46 L (150 in^3). Processing of the multichannel seismic reflection data used classical steps including CDP gathering (6-fold), binning at 25m, velocity analysis, stack and post-stack time migration. The maximum penetration is 1.5 to 2 s twtt. All the profiles presented here are time migrated and with a vertical exaggeration of 5. High-resolution swath bathymetry data was acquired with a maximum precision of 25 m using a hull-mounted multibeam echosounder system. The overall geometry of the active offshore fault system, including a full coverage bathymetric map, and one seismic profile collected are presented in Leroy *et al.* (2015). In this study, we focus on the Jamaica Passage and the interpretation of 60 seismic reflection profiles sampling the EPGFZ between Jamaica and Hispaniola (Fig. 5), including 9 key profiles that are shown here.

5. Stratigraphy and structure of the Jamaica Passage

5.1 Bathymetry

Fig. 6 presents a bathymetric map of the Jamaica Passage between Jamaica and Haiti. This bathymetric map highlights the most recent fault trace of the EPGFZ disrupting the seafloor, and crossing several distinctive morphological features from west to east: three basins with an average depth of 2500 m (the Morant, Navassa and Matley basins), three topographic highs north of the EPGFZ with an average depth of 500 m (the Holmes Bank, the Formigas Bank and the Navassa Ridge topped by Navassa Island) and three other topographic highs south of the EPGFZ with an average depth of 800 m (the Morant Ridge, the Albatros Bank and the Matley Ridge; Fig. 6).

5.2 Seismic reflection profiles

Our main purpose is to define the main stratigraphic sequences in the Jamaica Passage and characterize its tectonic feature, using the new collected data set. The definition of the seismic units and the stratigraphic correlation have been established with numerous seismic reflection profiles (see the coverage on Fig. 5) and not only with the six profiles shown in this paper. The correlative surfaces of the unit boundaries correspond to strong reflections, unconformities and distinctive patterns that we were able to correlate throughout the grids of seismic reflection data. Because of the slope drapes at basin flanks and topographic highs, and the distribution of the seismic profiles, correlation of seismic horizons from one basin to another cannot be done with the standard “loop-tying” method for 2D seismic reflection data (Herron and Latimer, 2011). However the characteristics of the seismic horizons are sufficient to allow “jump” correlation of marker beds between basins as done by Prather *et al.* (2012).

Based on morphological, structural and sedimentological criteria derived from the combined interpretation of the bathymetry and seismic data, we identify distinct crustal domains in the Jamaica Passage. The Fig. 5 shows the complete coverage of seismic profiles collected and interpreted here and highlights the profiles used to illustrate our key observations.

5.2.1 Acoustic basement

The top of the acoustic basement is defined as the most continuous and distinct high-amplitude horizon underlying the deepest sediments. This horizon is well marked by a distinct high-amplitude reflection (Fig. 7). The top of the acoustic basement underlying sediments, identified in the majority of the seismic profiles in the Jamaica Passage, is continuous. Beneath the top of the acoustic basement, the seismic basement (hereafter SB) shows two different facies related to its topography. At the base of the basins, the SB presents tilted parallel reflections (enlarged views 1 and 4, Fig. 7). Outside the basins, on topographic highs and ridges, the SB is more disrupted and chaotic, with local coherent parallel reflections (enlarged views 2 and 3, Fig. 7). That chaotic basement is not systematically observed below ridges with rugged sea-floor discards the possibility of velocity pull-up and pull-down artifacts. The inset map in Fig. 7 shows the continuous SB unit in the Jamaica Passage and the repartition of its two distinct facies.

The depth to basement map of the unit SB (i.e., sea level-top of SB unit interval), derived from all the seismic profiles reveals the presence of several basins in the Jamaica Passage (Fig. 8). The three deeper basins, well visible in the bathymetry (Fig. 6), have a top of the SB unit reaching in average 4.000 m-deep for the Morant and Matley Basins, and 3.200 m-deep for the Navassa Basin (Fig. 8). Three shallower basins, not easily visible in the bathymetric map, are identified with a top of the SB unit reaching in average 2.800 m-deep (Fig. 8).

5.2.2. Basin structures

The structure of the basins is revealed by the analysis of the sedimentary sequences and the depth to basement map along the seismic reflection profiles (Fig. 8). The westernmost basin, just at the toe of the southeastern tip of Jamaica, is the Albatros basin. This basin is bounded to the south by a strong escarpment of ~700 m (CMP #1800, Fig. 9a). Within the basin, we distinguish five seismic units (SB, U1, U2, U3 and U4) corresponding to the main phases of basin infilling. The seismic basement (SB unit, Fig. 9a) is clearly imaged beneath the basin around CMP #1500. This unit dips toward the south in the direction of the escarpment. A fan-shaped unit, denoted as U1 unit, overlies the SB unit, reaching a maximum thickness of about 0.5 s twtt. The onlap reflectors at the transition between SB and U1 exemplify that U1 lies unconformably on SB unit (Fig. 9a, CMP #1400). Above the U1 unit, the U2 unit infills the basin and lies conformably over U1. The U2 unit reaches a maximum thickness of about 0.35 s twtt and shows several parallel reflectors. The transition between U2 and the overlying U3 unit is marked by a strong reflection and a few onlaps. Another reflection, at the base of a facies with wider spacing between reflectors, defines the boundary between the U3 and U4 units. This transition is also marked by the onlap of the U4 unit reflections above the U3 unit (Fig. 9a). All the seismic units SB, U1, U2, U3 and U4 are deformed and folded. The units are uplifted on their southern side and are thus tilted toward the centre of the basin. Nevertheless, the escarpment, the tilted SB unit and the fan-shaped U1 unit, all indicate that the Albatros Basin could be a half-graben and the escarpment a former normal fault. Then the bathymetric escarpment could be the exposed fault scarp. Thus, SB corresponds to the pre-rift basement, the fan-shaped U1 unit may be interpreted as a syn-rift sequence with sediment thickness increasing toward the escarpment, while U2, U3 and U4 are isopach and could be interpreted as no normal fault-related sequences called post-rift. The deformation and the tilt of the units could indicate an inverse reactivation of the former normal fault. Fig. 9b shows a sketch illustrating how such a basin can be formed in scale 1:1. Step 1 shows the normal fault-related deposit of the U1 unit in an half-graben, called syn-rift. Step 2 is the time deposition of the flat unit U2 called the post-rift unit. Step 3 is the time deposition of the unit U3 in unconformity on the U2 unit than begins to be folded. The formation of onlaps at the transition U2/U3 (Fig. 9a) indicates that a context of compression began at this time during the U3 deposit. Step 4 shows the present-day configuration, and the deposition of the unit U4 in unconformity on the older folded units, during a second compressive episode. The half-graben is afterward inverted in a compressive context, and the former normal fault created by the first extensive phase may have been reactivated as a reverse fault during the compressive phases.

In the northeast of Albatros basin and west of the Jamaica Passage, the 4600 m-deep Morant basin is cross-cut by the EPGFZ. Fig. 10 provides details of seismic profile H12-036 (see Fig. 5 for location) showing that the Morant basin is also bounded to the south by a marked escarpment of ~1000 m (CMP #1700, Fig. 10). This basin is deformed between CMP #1550 and #1200 and that gives a transparent facies at depth. Fig. 11 presents enlarged excerpts of the profile pointing out the unconformities between the different seismic sequences. Five seismic units can be distinguished in the northern part of the profile (Fig. 10 and enlargement Fig. 11a). These units have the same characteristics than those identified and described in the Albatros Basin (Fig. 9), and are thus named with the same nomenclature: the SB unit is tilted toward the southern escarpment; the U1 unit is fan-shaped with a thickness increasing toward the escarpment; the U2 unit shows several parallel reflections; the transition between the U2 and U3 units is marked by a strong reflection and onlaps and the U4 unit onlaps the U3 unit. However, as the Morant Basin is cut by the strike-slip EPGFZ (CMP #1500 in Fig. 10 and Fig. 6), seismic units with different thicknesses could have been juxtaposed on either side of the fault by post-depositional motion, preventing to follow the U1, U2 and U3 units on both sides of the fault. Nonetheless, by comparing their characteristics the Morant Basin could originated as a half-graben similarly to the Albatros Basin. Enlargement of the U4 and U3 units located near the EPGFZ trace and presented in Fig. 11B shows the thickness variation of the unit U4 around the EPGFZ, which onlaps on the U3 unit. The unit U4 is thicker in the strike-slip furrow of the EPGFZ (CMP #1500), which indicates that the upper U4 unit was deposited during the activity of the EPGFZ.

The Matley Basin, east of the Jamaica Passage, displays similar characteristics (Fig. 12). This basin is also bounded by a prominent escarpment along its southeastern boundary. The interpretation of the seismic sequences shows same seismic units similar to there already identified in the Albatros Basin (Fig. 9) and in the Morant Basin (Fig. 10). Unlike the Morant Basin, the Matley Basin is cut by the

EPGFZ on its northwestern border (Figs. 6 and 12). Between CMP #800 and #1000, the sediments are deformed and folded, resulting in transparent facies in depth around CMP #800. Close to the escarpment, the sediments (around CMP #600) dip toward the NW, away from the escarpment. The sediments are tilted towards the centre of the basin indicating that the southeastern border of the basin has been uplifted. Sediments of the Matley half-graben show compressive deformation in the same way than in the Albatros and Morant half-grabens. In the Matley Basin, the infilling has a total thickness of about 1 s twtt near the CMP #600 (Fig. 12), apparently greater than along the profile of the Morant Basin. The profile crossing the Morant Basin is indeed shifted eastward with respect to the basin depocentre.

Between the Morant and Matley basins, the Navassa Basin exhibits distinct features compared to the Albatros, Morant and Matley half-grabens, both regarding its shape in map-view (narrower and more elongated) and its infilling (about three times less thickness of sediment). Figs. 13a and 13b show details of the H12-032 and H12-052 seismic profiles crossing the Navassa Basin. The sediment thickness in this basin is restricted to 0.3 s twtt on average, and the reflectors are strong, parallel and flat, without marked differences within the seismic sequence. The seismic profiles in the Navassa Basin show that the oldest units (U1, U2 and U3) of the Albatros, Morant and Matley basins are missing (Fig. 13). Thus the only seismic sequence identified is the more recent U4 unit, which directly overlies the seismic basement (SB unit). The thickness of U4, as presented in Fig. 13, may appear greater in the Navassa basin, but the thickness of U4 varies in the all basins as exemplified in the Morant basin (Fig. 10). Moreover, unlike the Morant and Matley basins that are obliquely crossed by the present-day trace of the left-lateral EPGFZ (Figs. 6, 10 and 12), the northern limit of the Navassa basin follows the trace of the fault (Figs. 6 and 13). Around CMP #12500 on Figs. 13a and 13b, the sediments of the U4 unit are slightly folded, as observed in the other basins. The seismic profiles indicate that we can not observe strike-slip fault segment in the south of the basin. The enlarged view of the bathymetric map, shown in Fig. 13c, highlights the straight and continuous EPGFZ on the northern side of the Navassa Basin, and its sinuous non-faulted southern border.

The identification of the units in the different basins was based on the characteristics of the seismic horizons and on the unit boundaries corresponding to strong reflections, unconformities and distinctive patterns. As we already emphasized, slopes and topography highs prevented us to apply the standard "loop-tying" method to correlate our units. However, we carried out a "jump" correlation of marker beds between basins. Fig. 14 presents a synthesis of the seismic stratigraphic correlation of the different seismic units between the Albatros, the Morant, the Navassa and the Matley basins.

5.2.3 A distinct crustal domain

At some distance from the basins, the seismic profiles yield a very different image of the sedimentary reflections (Figs.. 15 and 16). On these profiles, the reflections are chaotic or parallel and sub-horizontal, and always typified by strong reflections. Fig. 15 shows the seismic profile H12-053, situated in the south of the study area. The seismic interpretation of this profile highlights several seismic sequences: 1) an upper sequence, made up of strong and thick reflectors. The reflectors are parallel and overlie deformed seismic reflections resulting in a non-planar seafloor. This upper unit has a thickness of about 0.2 s twtt; 2) a second seismic sequence, about 0.5 s twtt thick, consisting of interbedded thin and strong reflectors. The reflectors are parallel in the lower part of the unit and more chaotic in the upper part; 3) a third sequence, consisting of strong parallel reflections in the upper part, with two pronounced reflectors, and a transparent facies in the lower part; 4) a lower sequence corresponding to a chaotic seismic sequence, including several strong and short curved reflectors. The second and third units are deformed and faulted.

Fig. 16 shows the seismic profile H12-022, situated at the extreme southeast of the study area. On this profile, the same seismic reflections are identified, and thus the same distinct seismic sequences may be defined. However, this seismic profile does not show deformation and faults affecting the seismic sequences.

One possible interpretation of this crustal domain, markedly different from the basin structures, is to relate it to the CLIP, identified, in the vicinity of our study area, on reflection seismic profiles, DSDP and ODP drills, and diving as described in Section 3.1 and shown in Fig. 3. However, because the seismic profiles in Fig. 3 are several hundreds of km apart from our profiles displayed in Figs. 15 and 16, we could only put forward the hypothesis that the crustal domain we image is possibly the CLIP as discussed in Section 6.4.

6 Discussion

6.1 Stratigraphy and origin of the half-grabens

In the Jamaica Passage area, no drills are available. It is thus difficult to correlate our seismic reflection units to known ages, and to propose a detailed stratigraphy of the area to explain the formation and the origin of the identified half-graben basins. One hypothesis may be that Morant and Matley basins, well expressed in the bathymetry and cross-cut by the EPGFZ, have been created by the fault during its strike-slip motion. However, the interpretation of the new seismic reflection dataset allows us to identify three other half-graben basins outside of the EPGFZ trace (the Albatros Basin south of the EPGFZ and two others basins north of the EPGFZ, Fig. 8). The Albatros Basin (Fig. 9) exemplifies a typical half-graben basin. These basins have the same seismic units than those of the Morant and Matley basins. All the identified basins are half-grabens with a fan-shaped seismic unit (U1) typical for a syn-rift deposition, and a normal fault escarpment on their south/southeastern side which trend about NE-SW (Fig. 17). These basins also show the same seismic units U2, U3 and U4 than those of the Morant and Matley basins. The presence of similar half-graben basins outside the trace of the EPGFZ does not support the hypothesis that the Morant and Matley basins were created by the EPGFZ activity. Another hypothesis could be to interpret these half-graben basins in relation with a previous extensional period, independent from the EPGFZ activity. The sedimentary and tectonic characteristics of the five half-grabens identified in the Jamaica Passage could be related to the characteristics of the half-graben basins encountered north of Jamaica and described in Leroy *et al.* (1996) as shown in Fig. 3a. By comparison, the Albatros, Morant and Matley basins sedimentary filling is thicker than that found between Cuba and Jamaica (1 s twtt *versus* 0.7 s twtt), which may be explained by the proximity of the sediment sources of Jamaica and Haiti. They also seem to be more deformed than those identified in the North Jamaica area. The resolution of the seismic reflection profiles and the acquisition methods are not the same between the two studies, making difficult to compare in detail the stratigraphy. Moreover, the Jamaica Passage is situated on the transpressive boundary between the Gonâve microplate and the Caribbean plate (Rosencrantz and Mann, 1991, Mann *et al.*, 1995), unlike the North Jamaica area which is on the Gonâve microplate interior, providing an explanation for the greater deformation observed in the Jamaica Passage. Another argument is provided onland in Jamaica by the Wagwater restraining bend, also interpreted to be an inverted half-graben coeval with the Cayman Trough margin rifting episode (Mann *et al.*, 1985; Mann and Bruke, 1990). We thus favor the hypothesis that the five half-grabens identified in the Jamaica Passage are coeval with the rifting episode that formed the passive margin of Jamaica from the early Paleocene to the early Eocene (Mann and Burke, 1990).

Using the geological field studies carried out in Jamaica and Hispaniola (*e.g.* Mann and Burke, 1990) and the marine geophysical surveys in the area (Dillon *et al.*, 1992; Calais and Mercier de Lépinay, 1995; Leroy *et al.*, 1996, 2000), we tentatively correlate the seismic units identified in the half-grabens of the Jamaica Passage with the known regional tectonic unconformities. The SB unit could correspond to the Mesozoic continental crust making up the pre-rift formations of the passive margin. The U1 syn-rift sequence could be correlated with the Paleocene and early Eocene sediments of the onshore Wagwater graben in Jamaica (Mann *et al.*, 1985). Moreover, the magnetic anomalies of the Cayman Trough oceanic crust indicate that the unconformity between the rifting episode (syn-rift deposits) and the spreading episode (post-rift deposits) represents an interval during the Ypresian (~49 Ma, Leroy *et al.*, 2000). This leads us to propose an age of ~49 Ma for the transition between the U1 syn-rift and U2 post-rift sequences. Following Wadge and Dixon (1984), the U2 post-rift sequence may correspond to the carbonate platforms (Yellow Limestone and White Limestone) identified on Jamaica.

6.2 Evidence for a first shortening phase

We already underlined that the half-grabens are deformed and folded. The seismic reflection profiles acquired across the Jamaica Passage provide a more detailed image of the post-rift sequence than that already observed for the Cayman Trough margin. In the Albatros, Morant and Matley basins (Figs. 9, 10, 11, 12), the unit U2 is deformed indicating a phase of tectonic shortening recorded in the three basins. Specifically, the unconformity between the U2 and U3 post-rift sequences could correspond to the regional tectonic rearrangement recorded in the early Miocene (about 20 Ma, Calais and Mercier de Lépinay, 1995; Pindell and Barrett, 1990), coeval with a southward jump of the Cayman Trough spreading centre (Leroy *et al.*, 2000). This rearrangement led to a prominent sedimentary unconformity cropping out onshore in southeast Cuba and on Hispaniola, as well as offshore in the Windward Passage along the SOFZ (Calais and Mercier de Lépinay, 1995). This prominent unconformity has long been interpreted as the result of folding and uplift of the basement due to the oblique collision with the Bahamas platform (*e.g.*, Pindell and Barrett, 1990).

6.3 Structure and deformation related to the strike-slip EPGFZ

The U4 unit is the only sedimentary sequence that we can identify in the Navassa Basin (Figs. 13 and 14). Mann *et al.* (1995) interpreted this basin as a pull-apart basin bounded to the north and the south by two offset segments of the EPGFZ (Fig. 4). The recent bathymetry data (Fig. 6) indicate that the trace of the EPGFZ can only be followed along the northern edge of the rectangular-shaped Navassa Basin. The seismic profiles (Fig. 13) also clearly indicate that no strike-slip fault segment is present to the south of the basin.

This leads us to interpret it rather as an asymmetrical strike-slip related basin. Such types of asymmetrical basin have been identified along several strike-slip faults, for example, along the North Anatolian Fault in the Marmara Sea (Seeber *et al.*, 2010; Choi *et al.*, 2011) in the vicinity of typical pull-apart basins (Armijo *et al.*, 2002), along the Dead Sea Fault (Ben-Avraham and Zoback, 1992) and along the Polochic Fault in Guatemala (Ben-Avraham, 1992). We thus interpret the unit U4 as a syn-tectonic sequence deposited during the activity of the EPGFZ. Based on conventional field geology and the identification of local unconformities, the onset of activity of the EPGFZ is estimated to be middle Miocene (Draper, 1987) to late Miocene (14 Ma, James-Williamson *et al.*, 2014) in Jamaica, and early Miocene in Haiti (Calmus, 1983).

The trace of the EPGFZ cuts across the proposed inherited Morant and Matley basins (Figs. 6, 10 and 12). Figs. 10 and 11b show that the unit U4 is thicker within the strike-slip furrow of the EPGFZ (CMP #1600) than at distance away from the fault trace (CMP #1400). This observation as well indicates that the EPGFZ was active during the deposition of the upper U4 unit. The Morant and Matley half-graben basins are thus further deformed by the activity of the EPGFZ. Similar observation was done by onland field surveys in Jamaica where the activity of the EPGFZ in the middle Miocene overprints the older extensional structures (James-Williamson *et al.*, 2014). In all the proposed inherited half-grabens, even outside the trace of the EPGFZ, like in the Albatros Basin (Figs. 9, 10, 11, 12), the U4 unit is deformed and folded and is unconformable on the older U3 unit. This indicates a phase of shortening across the Jamaica Passage during the activity of the EPGFZ. This shortening witnesses the transpressive tectonics along this plate boundary. The present-day oblique motion between the Caribbean and North American plates, converging in an ENE-WSW direction at about 20 mm/yr, is accommodated by several active faults and folds in and around Hispaniola (Mann et al., 1995). The EPGFZ is one of the major structure accommodating ~7 mm/yr of pure strike-slip motion (Manaker et al., 2008). However, recent block modeling based on GPS velocities (Calais et al., 2010; Benford et al., 2012b; Symithe et al., 2015) predict along the EPGFZ, a component of fault-normal convergence in addition to the main strike-slip motion. The magnitude of this fault-normal component varies between the models depending on the geometry of the blocks and the data set, but suggests significant transpression on the EPGFZ. In the Jamaica Passage, the primary structures of the EPGFZ are a series of strike-slip fault segments associated to geomorphic features highlighting a primary strike-slip motion (Leroy et al., 2015). Our seismic and structural study of the Jamaica Passage evidences an asymmetrical strike-slip related basin (the Navassa Basin, Fig. 13) that attests as well of the primary strike-slip motion of the EPGFZ.

The block models predict fault-normal and fault-parallel components on block boundaries, the blocks being rigid. Their hypothesis is thus that the deformation (strike-slip and compressive) is entirely localized on the block boundaries, here the EPGFZ. Benford et al. (2012b) nonetheless acknowledge that the fault-normal convergence predicted by their model is partitioned onto the EPGFZ and structures north and possibly south of the fault zone. We evidence some shortening in the Jamaica Passage, not only in the two half-graben Basins crosscut by the EPGFZ, but also in the Albatros Basin, south of the trace of the EPGFZ. However, to constrain the plate motion partitioning of the deformation between fault-normal convergence and strike-slip motion, the structures north of the EPGFZ have to be investigated, and particularly the Gulf of Gonâve, the offshore prolongation of the Haiti fold-and-thrust belt (Mann et al., 1995).

6.4 Possible presence of the CLIP close to the Jamaica Passage

At distance from the basins, in the southeast of the Jamaica Passage, the seismic profiles display markedly distinct characteristics from the basin structures. The bathymetric map (Fig. 6) also shows that the seafloor appears to be rougher here than in the area where we mapped the Cayman-related inherited basins. In the vicinity of the Jamaica Passage, in the Lower Nicaraguan Rise, in the Colombian Basin and in the Beata Ridge, the CLIP was previously identified thanks to the presence of the Caribbean typical reflectors and confirmed by drilling (DSDP and ODP) and submersible dives (Fig. 3). We propose that the seismic sequences identified in the southeast of the Jamaica Passage and shown in Fig. 15 and 16 could image the CLIP. The four seismic sequences, described in Section 5.2.3, display similar characteristics with the reflectors typifying the CLIP as shown in Fig. 3. We put forward the hypothesis that these sequences could correspond to the typical horizons of the CLIP. The upper unit shown in Fig. 15 and 16 could correspond to the uppermost sequence of the CLIP lying upon the eM horizon. The intermediate unit could be correlated with the sequences containing the typical A" and B" reflectors. Finally, the curved reflectors imaged in the lower unit could be correlated with the V horizons of the CLIP as proposed by Mauffret and Leroy (1997).

6.5 Tectonic implications

Following our proposed interpretations, the Jamaica Passage consists of two pre-existing crustal domains – the Eastern Cayman Trough passive margin and the CLIP – for which we propose a new structural scheme (Fig. 18). The Albatros, Morant and Matley basins, identified in the Jamaica Passage, are interpreted as half-grabens of the Eastern Cayman Trough margin. The presence of tilted blocks belonging to the Eastern Cayman Trough passive margin has already been proposed in the eastern part of the Gonâve microplate based on paleotectonic reconstructions and magnetic mapping (Pubellier *et al.*, 2000). The easternmost tilted block of the Eastern Cayman Trough passive margin imaged in previous surveys was the Holmes bank (Fig. 2) near northeast Jamaica (Leroy *et al.*, 1996), but we propose here that this continental passive margin extends at least as far as the Matley Basin near the southwestern tip of the Southern Peninsula of Haiti. In the southern part of the Jamaica Passage, the interpretation of the seismic profiles with the typical seismic reflectors (A'', B'' and V) could indicate that the CLIP is present up to the southern part of the Jamaica Passage, at the extreme northeast of the Lower Nicaraguan Rise.

In our interpretations, the EPGFZ does not follow the limit between these two domains displaying distinct crustal rheologies. The EPGFZ cuts obliquely across the rheological boundary and also across the pre-existing half-grabens. As a consequence, tectonic inheritance does not seem to have played a major role in the mechanical processes involved with the localization of the present trace of the EPGFZ. Such an observation is reported along the trace of the very few major strike-slip faults known to have propagated such as the North Anatolian Fault (Armijo *et al*., 1999) or the Altyn Tagh Fault (Peltzer and Tapponnier, 1988; Meyer *et al.*, 1998). The stress concentrations at the propagating fault tips are often thought to explain why such fault cut across rheological boundaries rather than progressively coalescing at the boundary between domains with contrasted rheologies (Hubert-Ferrari *et al*., 2003). While we are lacking any direct evidence substantiating the propagation of EPGFZ, its linear trace and actual localization cutting across very distinctive rheological domain suggest it has been the case.

7. Conclusions

We imaged distinct structures in the Jamaica Passage thanks to high-resolution bathymetry and seismic reflection data. We propose to interpret the half-grabens basins structures evidenced as created during the Cayman margin rifting episode, thus delineating the easternmost part of the Cayman Trough passive margin. These half-grabens have been deformed and folded afterward during a phase of compression that could be related to a regional paleogeographic rearrangement at about

20 Ma. In the south of these half-grabens, a distinct crustal domain is characterized by strong horizontal parallel reflectors, possibly indicating the presence of Carib Beds typical of the CLIP. The activity of the left-lateral strike-slip EPGFZ led to the formation of the Navassa asymmetrical strike-slip related basin and is imaged in the Morant half-graben. All the inherited basins are deformed during the activity of the EPGFZ indicating a compressive phase across the Jamaica Passage, related to the transpressive tectonics along this plate boundary. Finally the trace of the EPGFZ does not seem to be influenced by tectonic inheritance, since the transition between the two crustal domains does not appear to represent a zone of weakness for fault localization.

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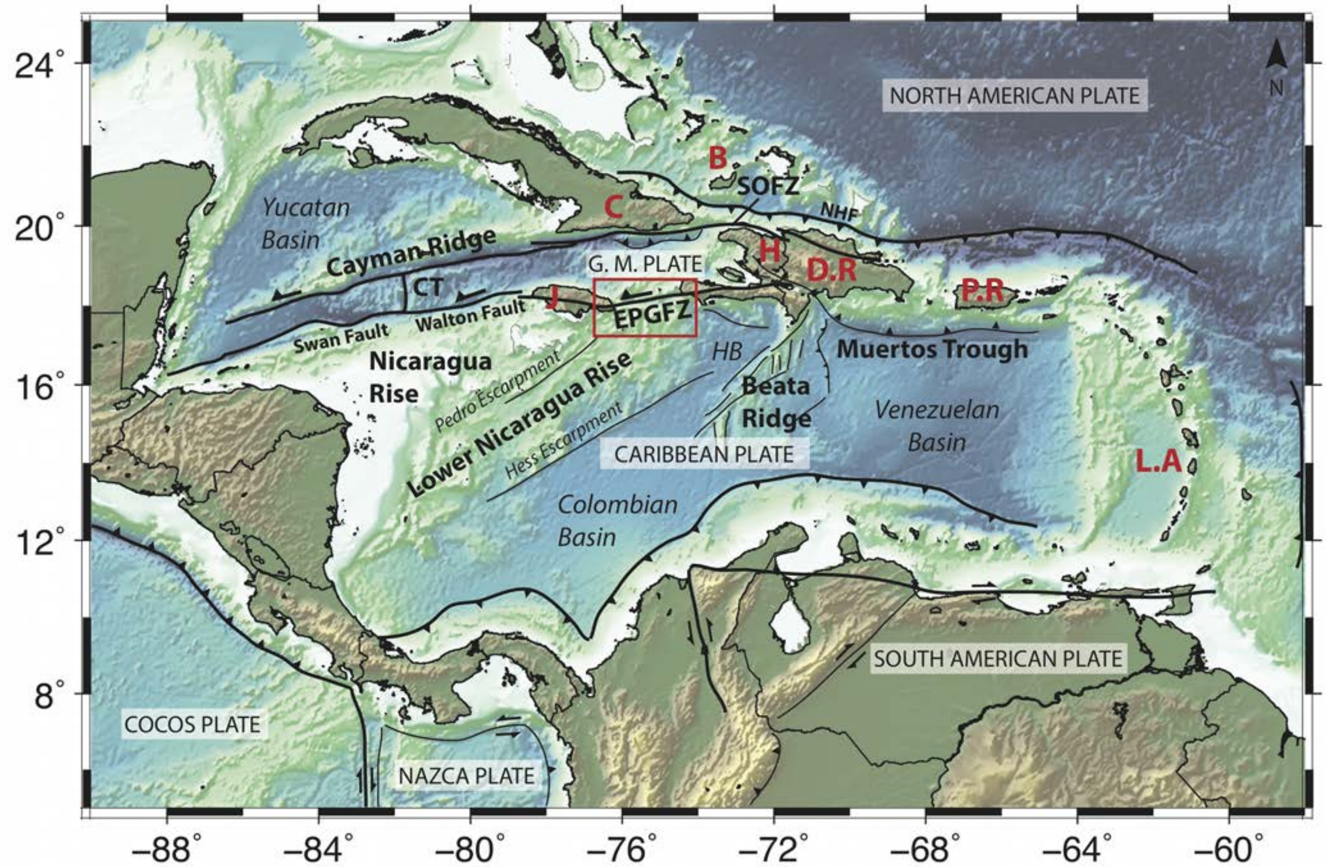


Figure 1: Tectonic map of the Caribbean. CT: Cayman Trough, EPGFZ: Enriquillo-Plantain-Garden Fault Zone, SOFZ: Septentrional-Oriente Fault Zone, NHF: North Hispaniola Fault, C: Cuba, J: Jamaica, B: Bahamas, H: Haiti, D.R: Dominican Republic, P.R: Puerto Rico, L.A: Lesser Antilles, G. M. PLATE: Gonâve micro-plate, HB: Haitian sub-basin. The red rectangle indicates the study area. Topography and bathymetry are from the 2 arc-minute global relief of Earth's surface ETOPO.

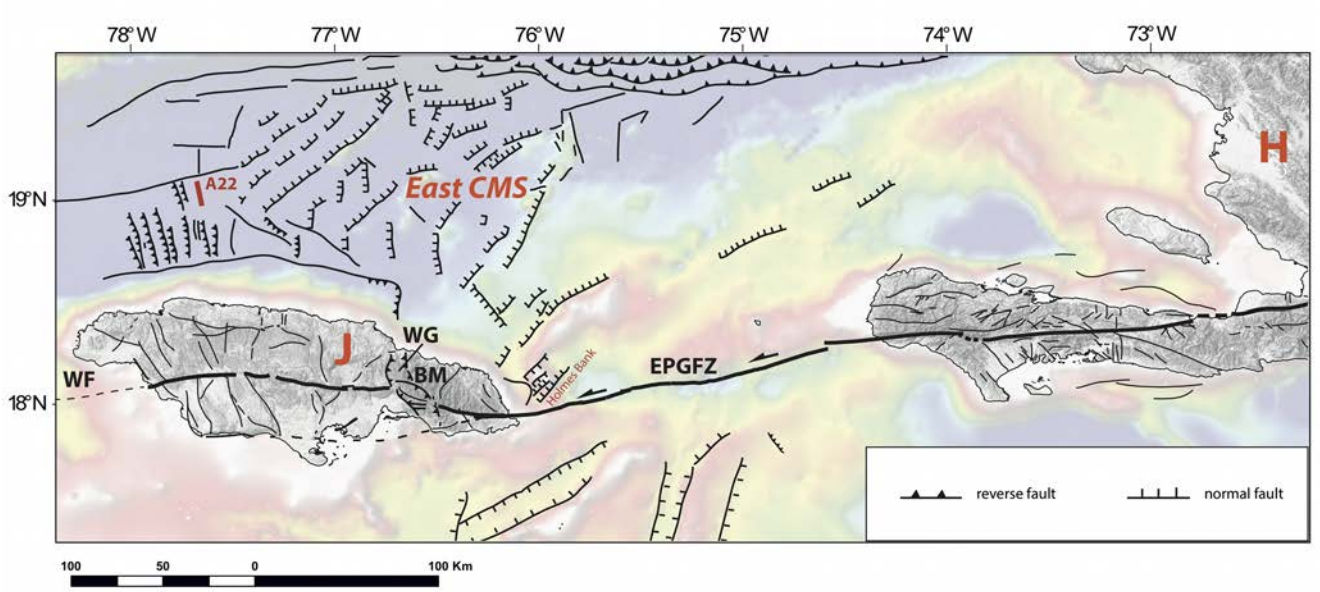


Figure 2: Synthetic structural map of the study area. Faults are from Bien-Aimé Momplaisir (1986), Calais and Mercier de Lépinay (1991), Leroy *et al.* (1996 and 2000), Granja Bruña *et al.* (2011) and Benford *et al.* (2012a). J: Jamaica, H: Hispaniola, East CMS: Eastern Cayman Margin System. WF: Walton Fault, WG: Wagwater Graben, BM: Blue Mountains, HB: Holmes Bank, EPGFZ: Enriquillo-Plantain-Garden Fault Zone. A22: magnetic anomaly 22 (~49 Ma, Leroy et al., 2000).

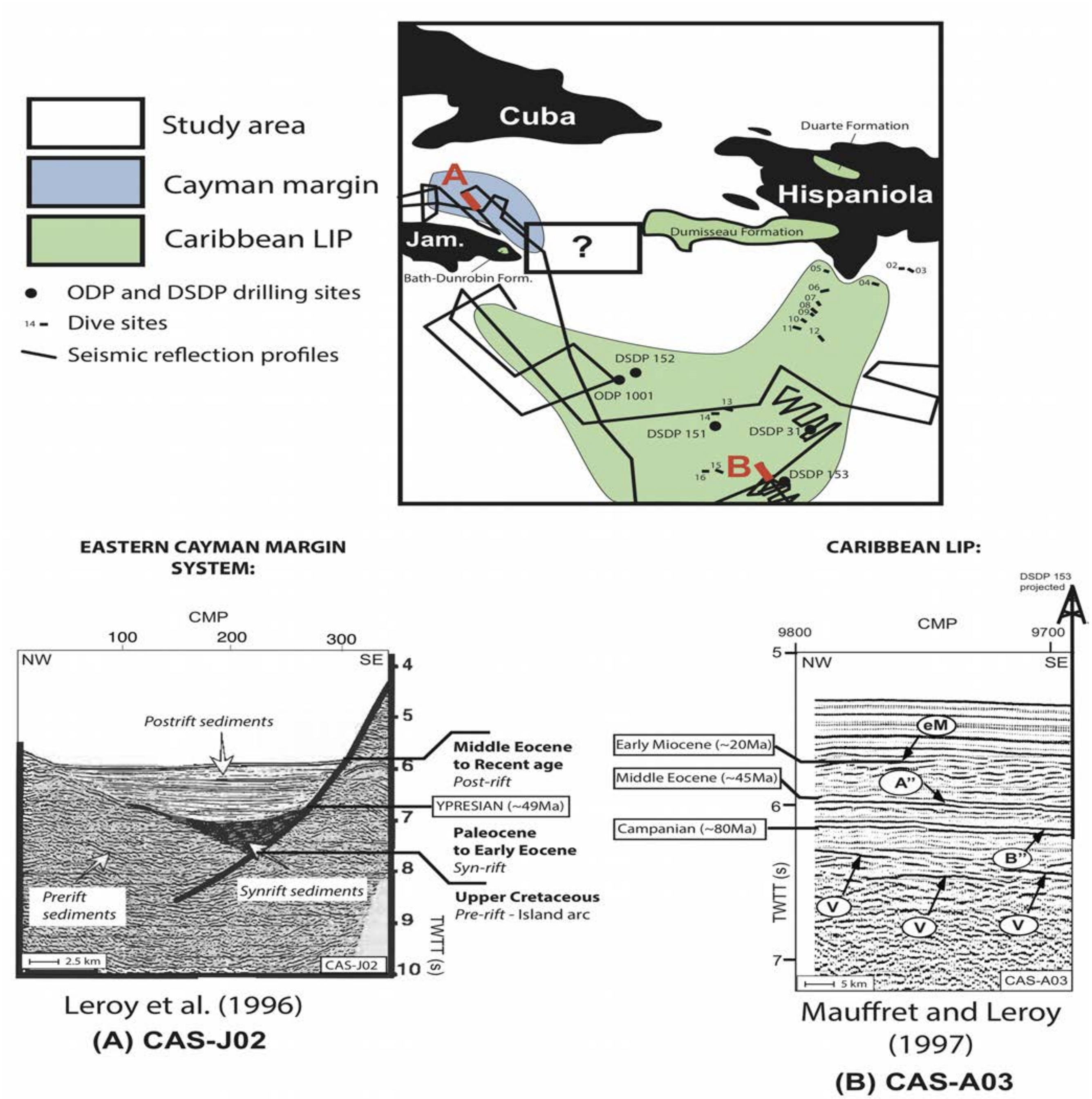


Figure 3: Map of the extent of the identified Caribbean LIP and eastern Cayman Trough passive margin. The identification of the Caribbean LIP is based on offshore on reflection seismic profiles, DSDP and ODP drills and submersible diving (Edgar *et al.*, 1973; Mauffret and Leroy, 1997, Mauffret *et al.*, 2001) and is based onshore on outcrops (Sen *et al.,* 1988; Hastie *et al.*, 2008). The identification of structures of the eastern Cayman Trough passive margin is based on reflection seismic profiles and correlations with onshore formations in Jamaica (Leroy *et al.*, 1996). Published seismic stratigraphic sequences (A) in North Jamaica (Leroy *et al.*, 1996; CAS-J02) and (B) in the Caribbean LIP (Mauffret and Leroy, 1997; CAS-A03). See text for detailed description of the seismic units.

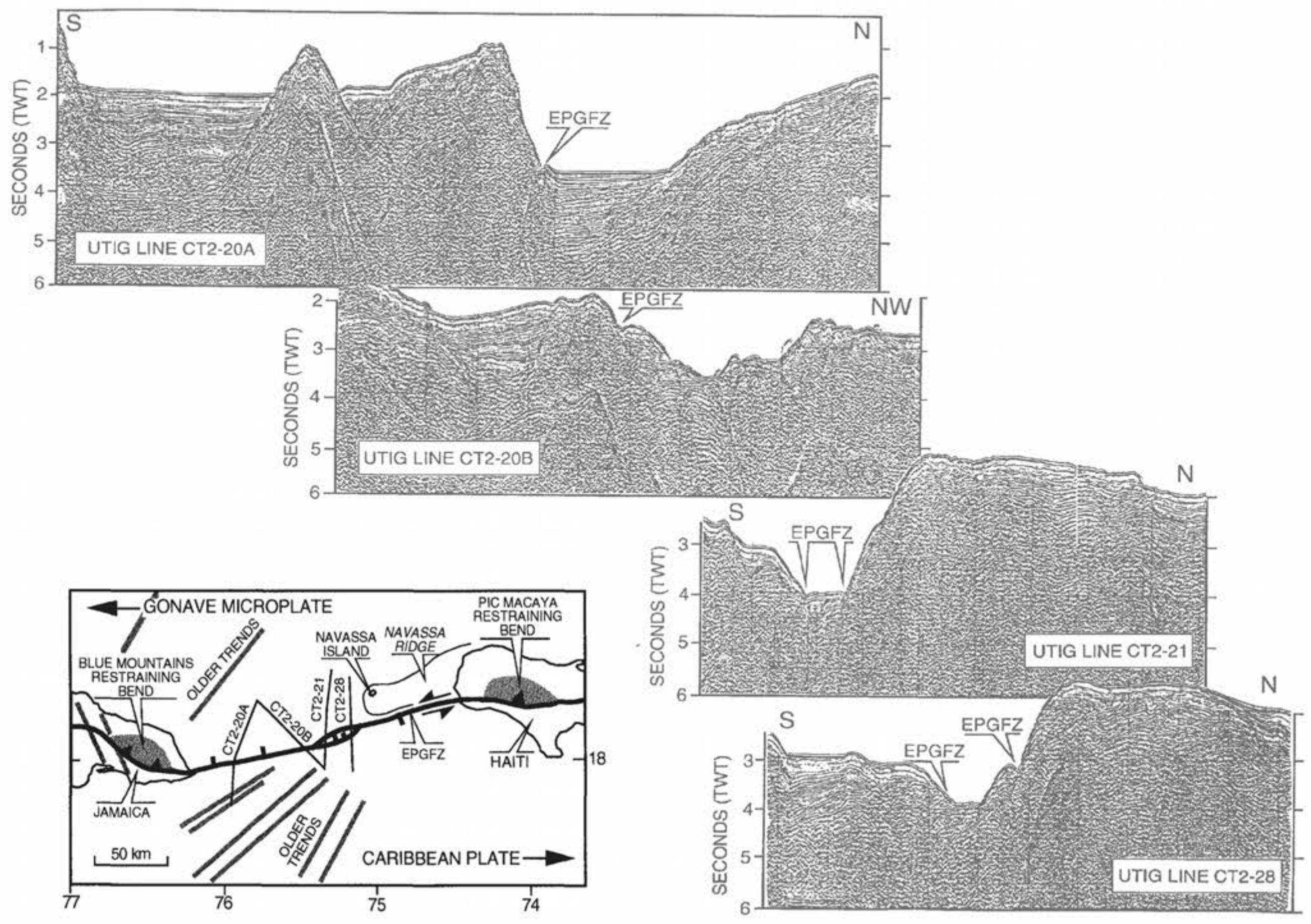


Figure 4: Four seismic reflection lines and the proposed trace of the EPGFZ in the Jamaica Passage from Mann *et al.* (1995). The positions of the four seismic profiles are also displayed in Fig. 5.

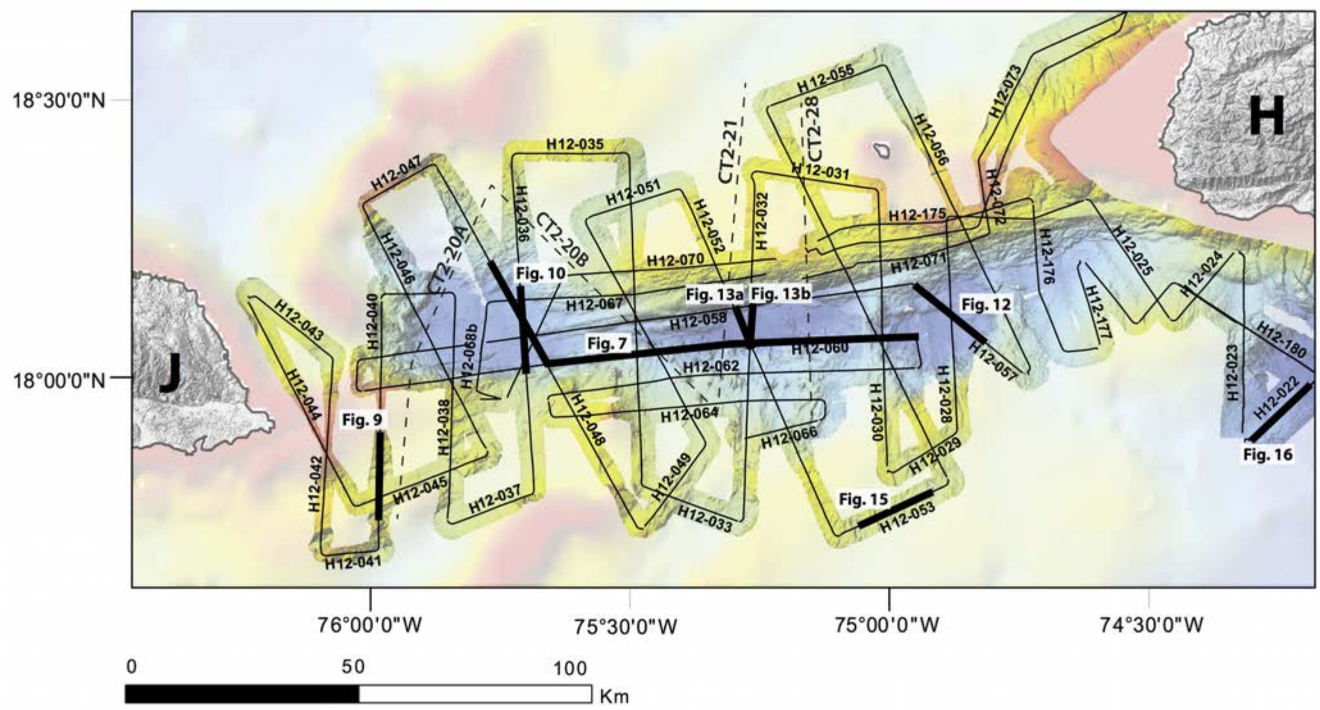


Figure 5: Track map of the HAITI-SIS cruise in the Jamaica Passage drown on the bathymetric map. J: Jamaica; H: Hispaniola. The thick solid lines represent the location of the interpreted seismic profiles showed in this paper. The dashed lines are the tracklines of the four seismic reflection profiles reported in Mann *et al.* (1995) and shown in Figure 4.

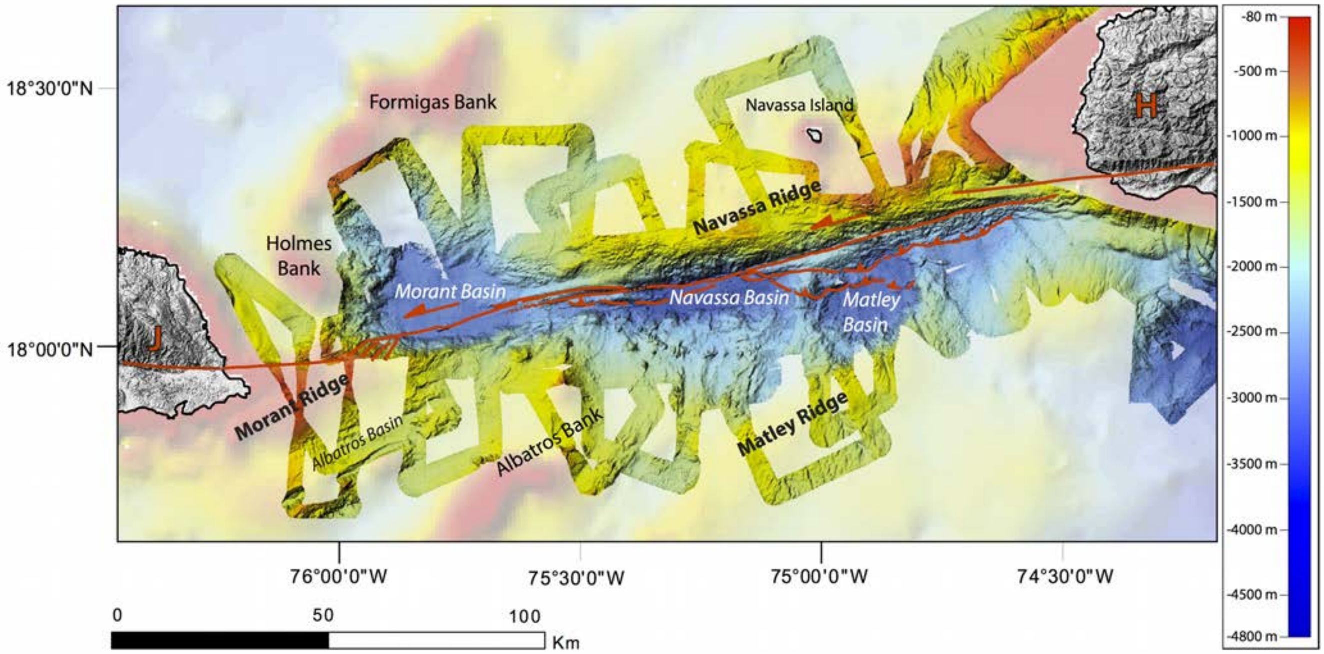


Figure 6: High-resolution bathymetric map of the Jamaica Passage and nomenclature of the major physiographic features. Main active EPGFZ structure is shown in red (Leroy *et al.*, 2015). J: Jamaica, H: Hispaniola. The red line represents the present active trace of the Enriquillo-Plantain-Garden Fault Zone (EPGFZ).

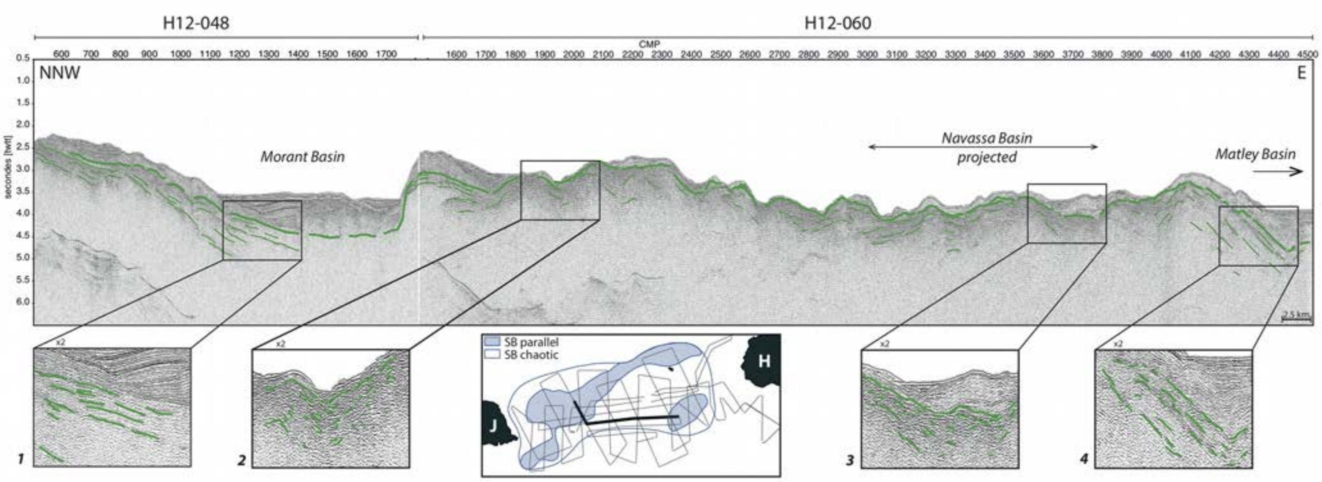


Figure 7: Interpreted seismic profiles HT12-060 and HT12-048 showing the continuous top of the acoustic basement (heavy green line) and the seismic basement below (SB unit, thin green lines). Enlarge views of the SB unit show its different facies: views 1 and 4, parallel facies; view 2 and 3, chaotic facies. See Fig. 5 for detailed location of the seismic profiles. The inset map shows the repartition of the two distinct facies of SB in the Jamaica Passage.

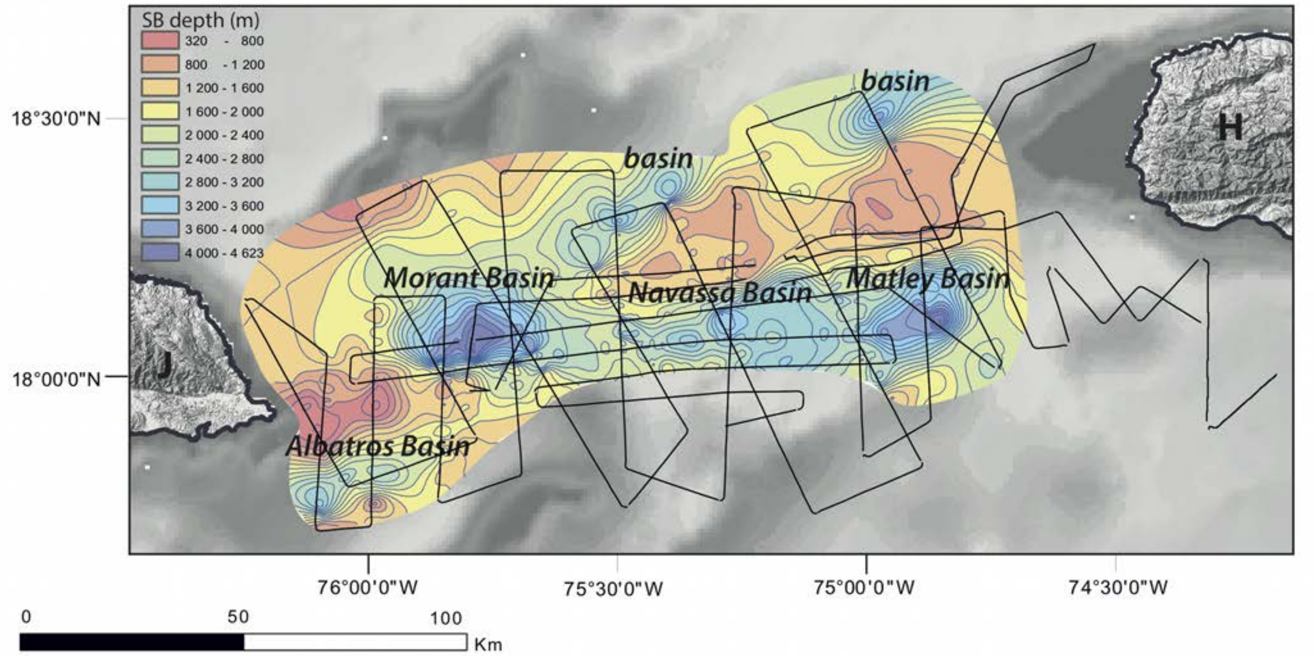


Figure 8: Depth to basement map. The basement is defined as the top of the seismic unit SB (see text for explanations). The color scale indicates the depths in meters that are interpolated from the dense seismic coverage. Depths are calculated with a velocity of 1500 m/s for the water layer (sea level-sea bottom interval) and 2200 m/s for sediments (seafloor-top of SB unit interval). The contour interval is 200 m. The thin lines represent the tracklines of the seismic profiles. J: Jamaica; H: Hispaniola.

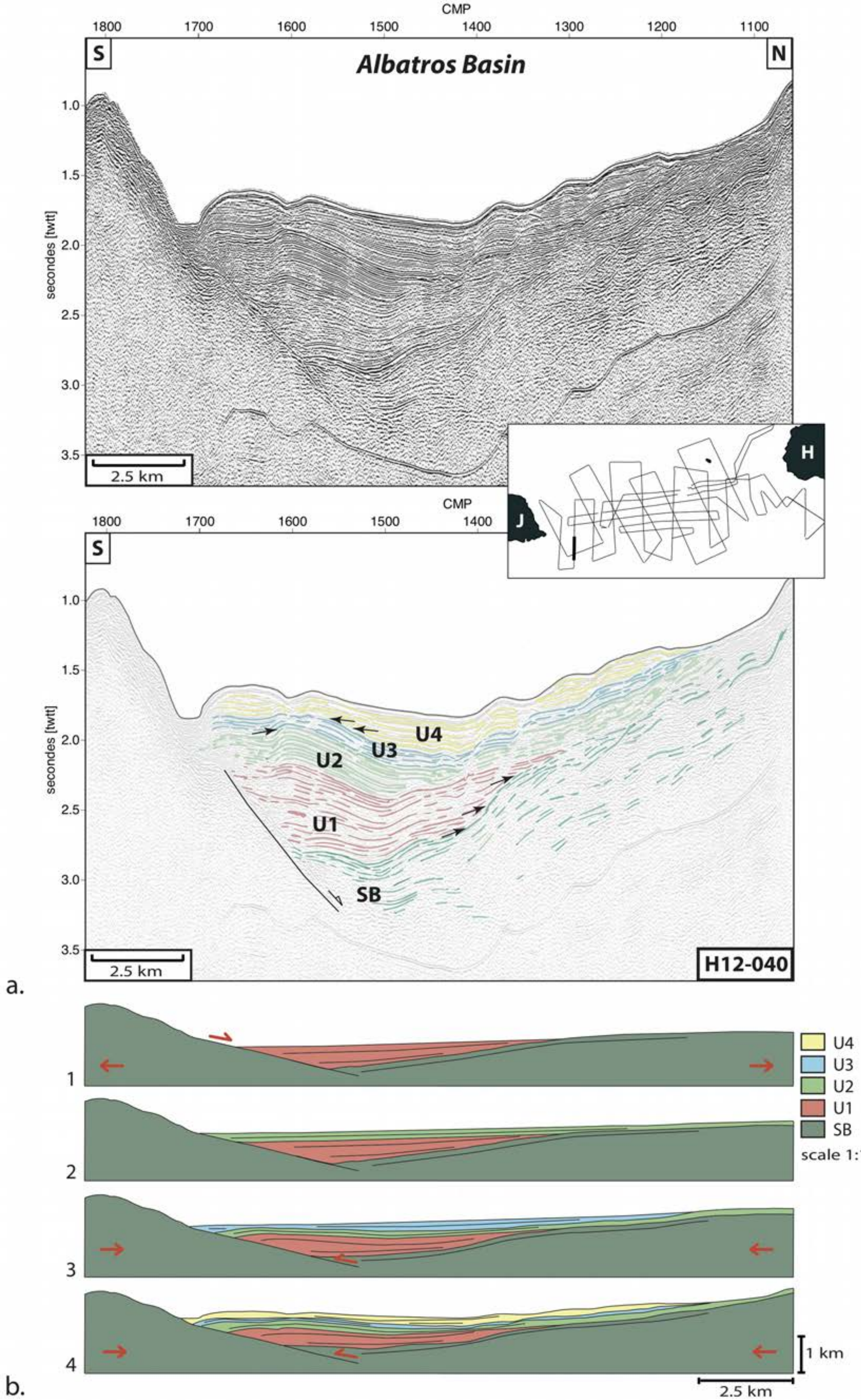

CMP
1800
1700
1600
1500
1400
1300
1200
1100
S
N
Albatros Basin
secondes [twtt]
1.0
1.5
2.0
2.5
3.0
3.5
2.5 km
H
J
U4
U3
U2
U1
SB
H12-040
a.
1
2
3
4
scale 1:1
1 km
b.

Figure 9: a. Detail of seismic profile H12-040 (upper panel) and its interpretation (lower panel). Black arrows show unconformities and onlaps. See inset and Fig. 5 for location. b. Sketch of the formation of the Albatros Basin at scale 1:1. Small topographic steps between CMP 1200-1400 correspond to gravitational unrooted normal faults without regional kinematics significance. See text for a detailed description in Section 5.2.2.

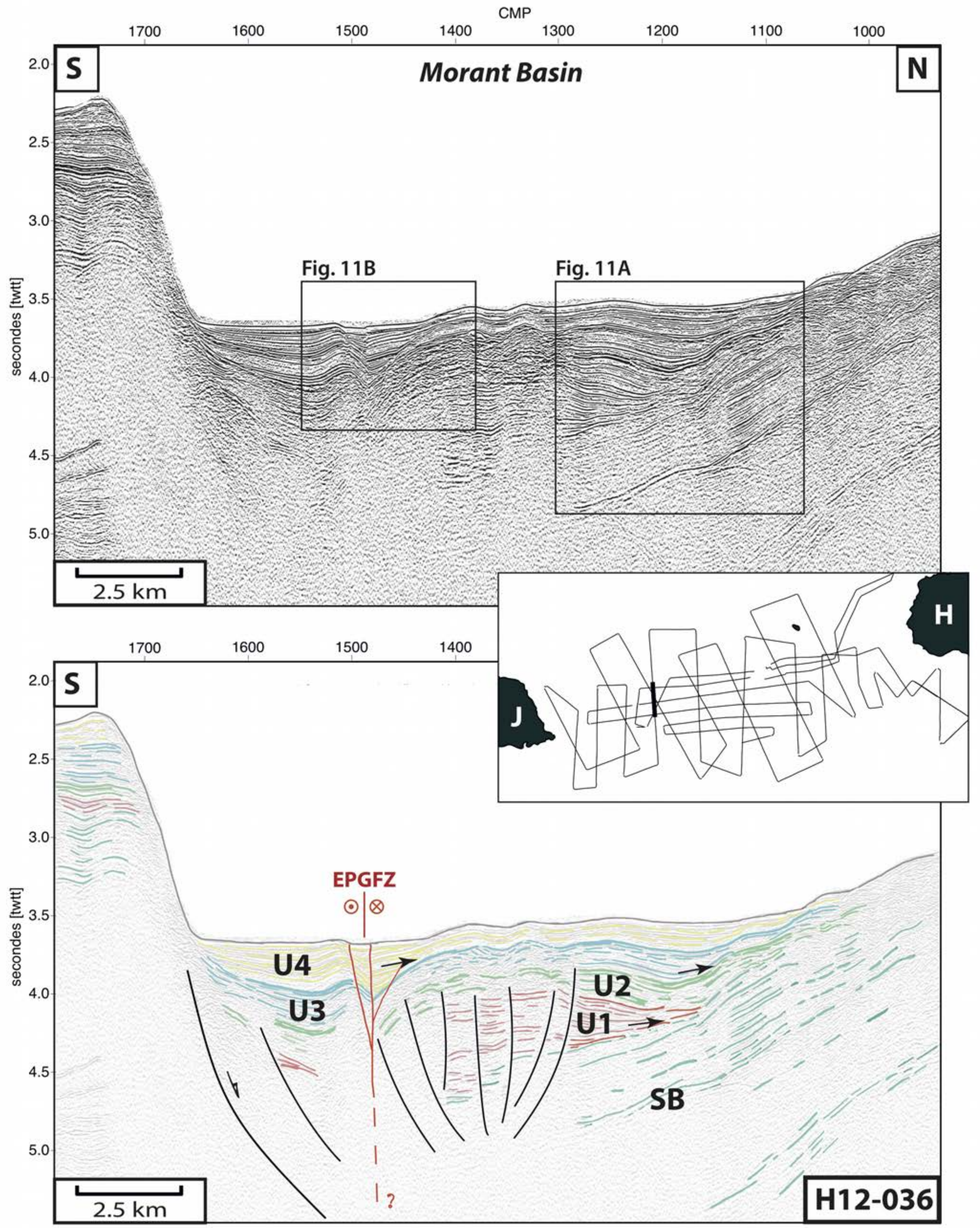

CMP
1700
1600
1500
1400
1300
1200
1100
1000
S
Morant Basin
N
2.0
2.5
3.0
3.5
4.0
4.5
5.0
secondes [twtt]
Fig. 11B
Fig. 11A
2.5 km
H
J
S
EPGFZ
U4
U3
U2
U1
SB
?
H12-036

Figure 10: Detail of seismic profile H12-036 crossing the Morant Basin (upper panel) and its interpretation (lower panel). Black arrows show unconformities and onlaps. See inset and Fig. 5 for detailed location.

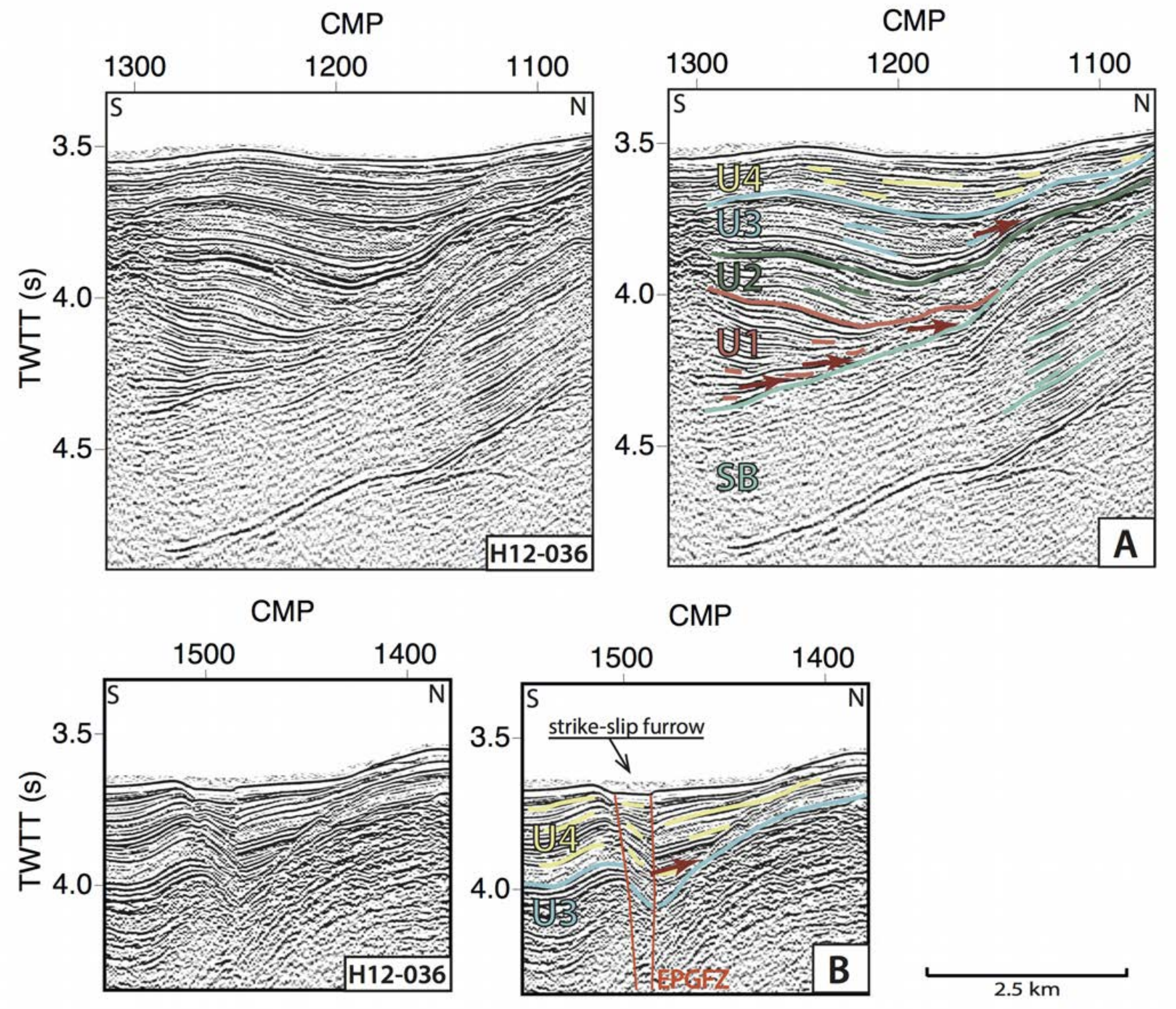


Figure 11: Enlarged images of the unconformities between the seismic units identified on profile H12-036. See Fig. 10 for close-up locations. A: unconformities and onlaps (red arrows) between the SB and U1 units, and between U2 and U3 units. B: unconformity and onlaps (red arrows) between the upper units U3 and U4. The red lines indicate the present-day position of the EPGFZ.

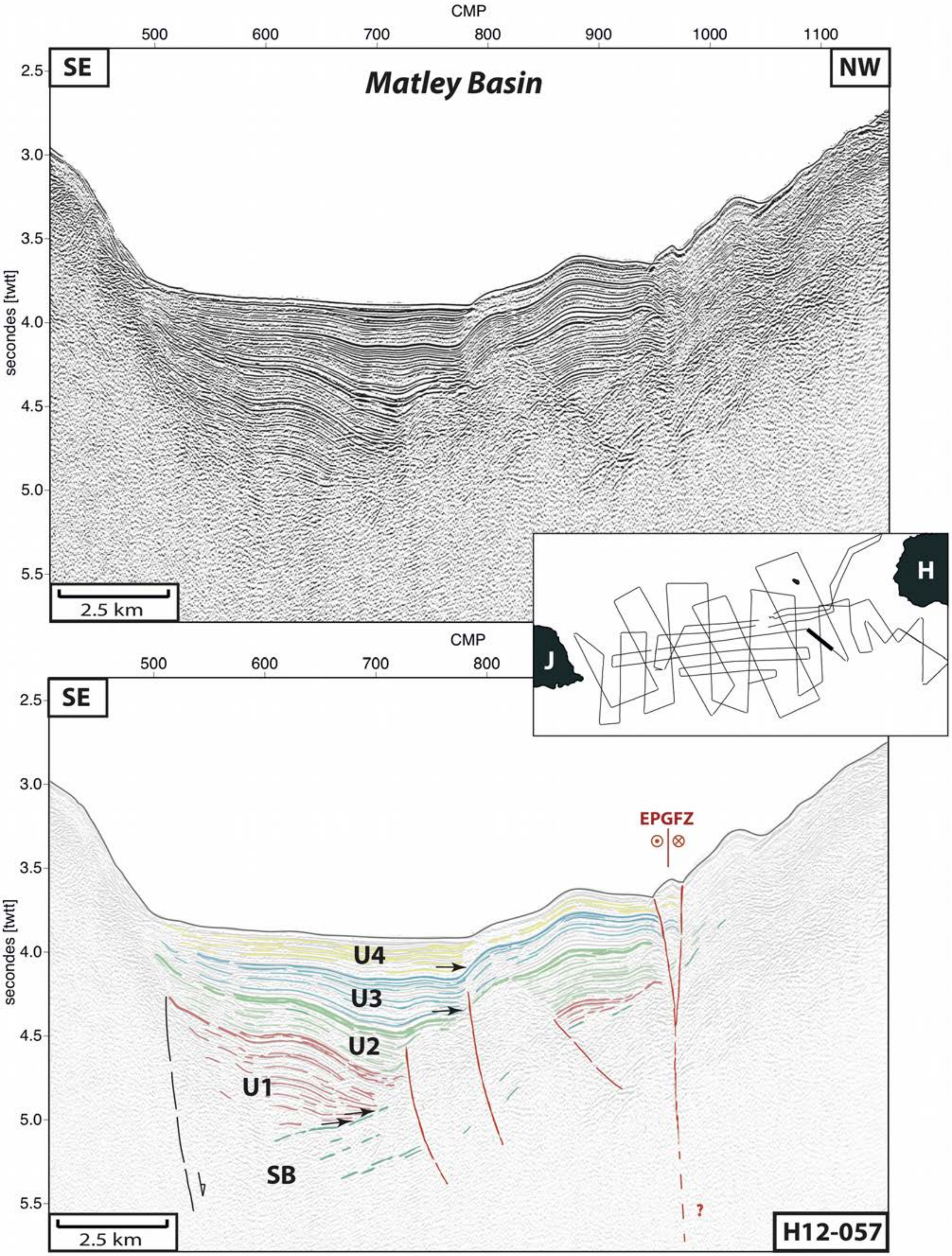
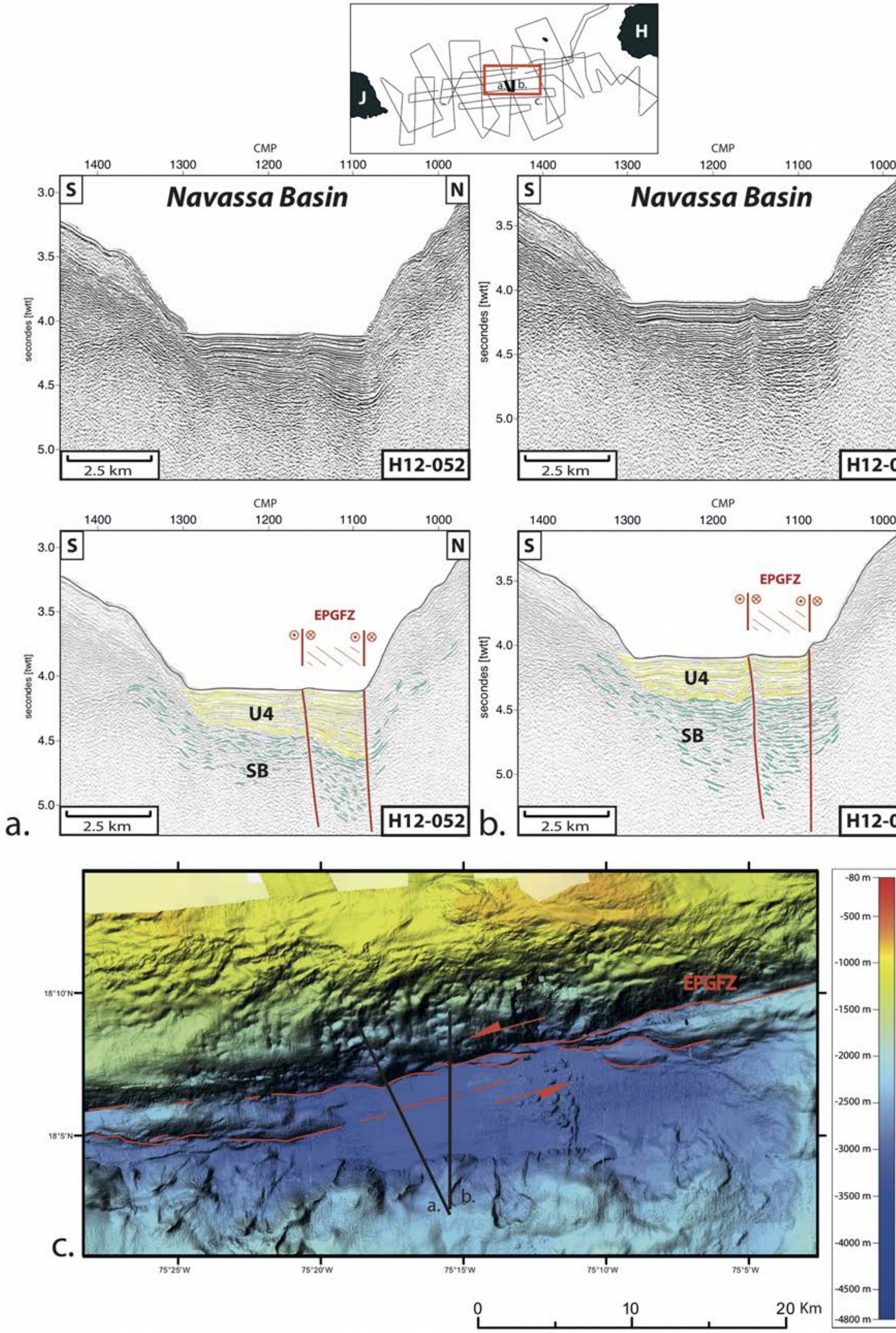

CMP
SE
NW
Matley Basin
secondes [twtt]
2.5 km
H
J
EPGFZ
U4
U3
U2
U1
SB
?
H12-057

Figure 12: Detail of seismic profile H12-057 crossing the Matley Basin (upper panel) and its interpretation (lower panel). Black arrows show unconformities and onlaps. See inset and Fig. 5 for location.



H
J
a.
b.
c.
CMP
1400
1300
1200
1100
1000
S
N
Navassa Basin
seconds [twtt]
2.5 km
H12-052
H12-032
EPGFZ
U4
SB
18°10'N
18°5'N
75°25'W
75°20'W
75°15'W
75°10'W
75°5'W
0
10
20 Km
-80 m
-500 m
-1000 m
-1500 m
-2000 m
-2500 m
-3000 m
-3500 m
-4000 m
-4500 m
-4800 m

Figure 13: **a**: Detail of seismic profile H12-052 crossing the Navassa Basin (upper panel) and its interpretation (lower panel). b: Detail of seismic profile H12-032 crossing the Navassa Basin (upper panel) and its interpretation (lower panel). c: Enlarged view of the bathymetric map. See inset and Fig. 5 for location.

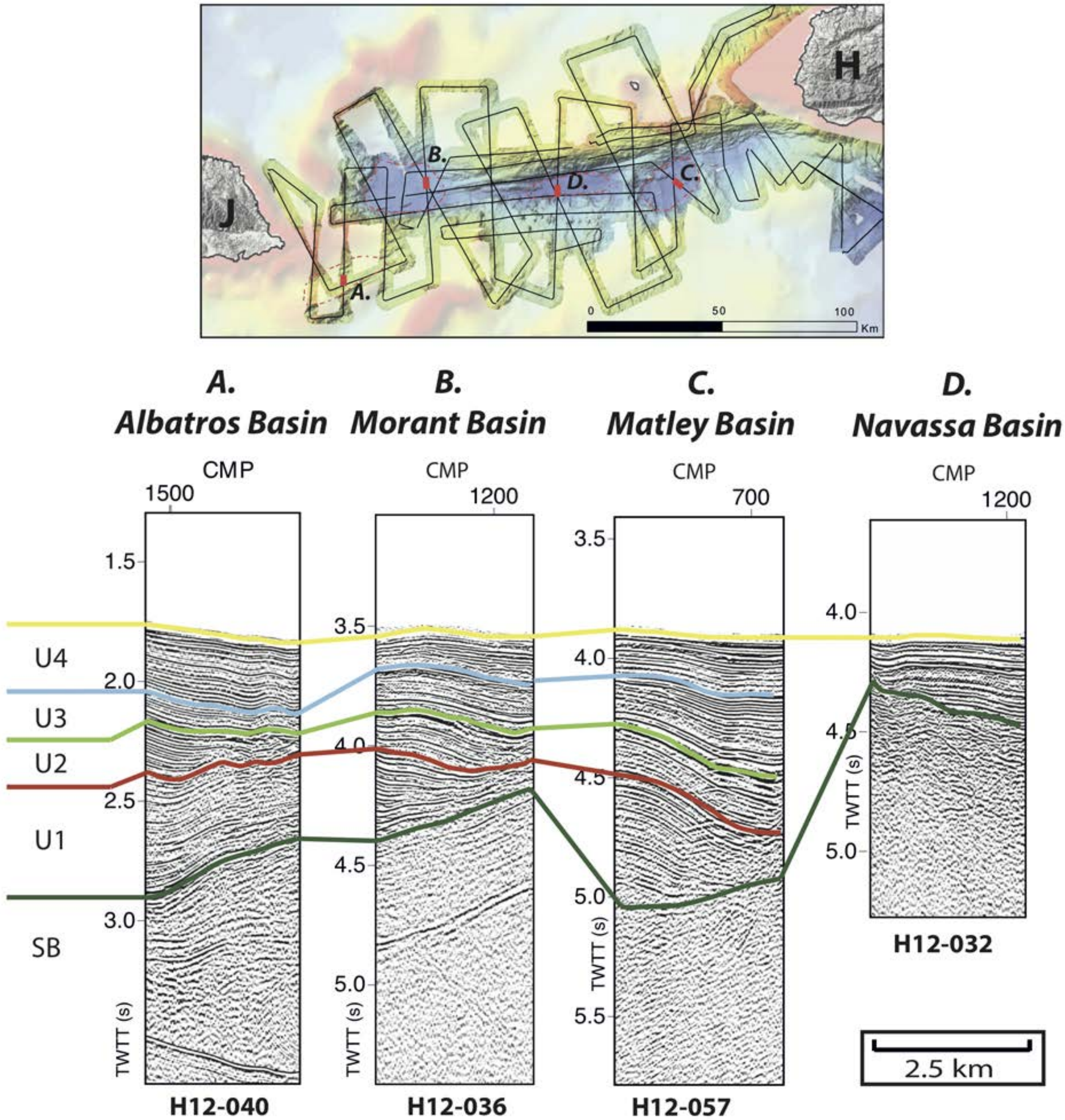


Figure 14: Synthesis of the seismic sequences identified in the three major basins of the Jamaica Passage, and seismic facies correlation between the four basins. In the Navassa Basin, only the upper sequence U4 is identified overlying the acoustic substratum SB. Red dotted lines in the map show the locations of the basins.

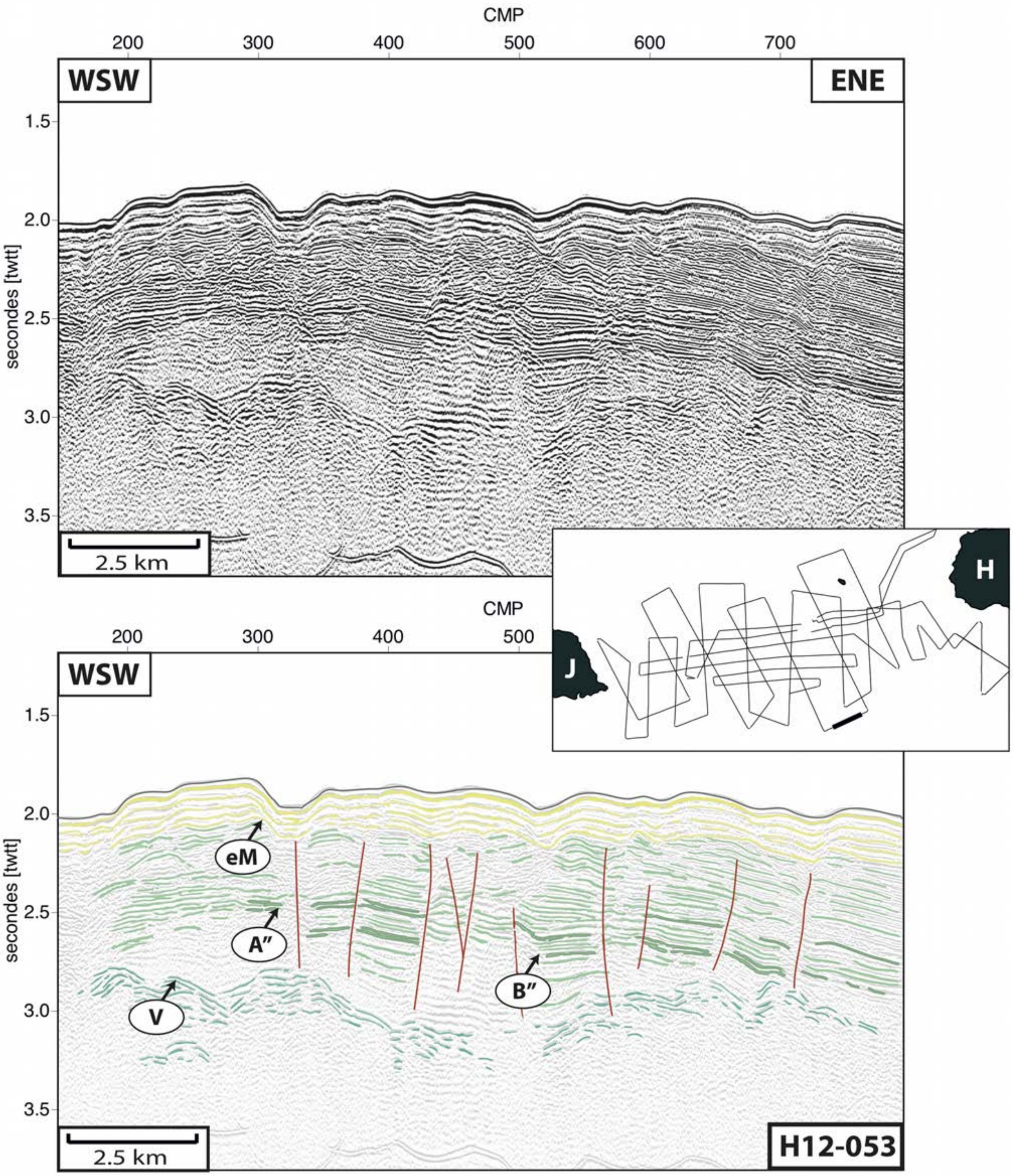


Figure 15: Detail of seismic profile H12-053 (upper panel) and proposed interpretation (lower panel). The different units identified are CLIP-type (Caribbean Large Igneous Province): eM, A", B" and V. See inset and Fig. 5 for location.

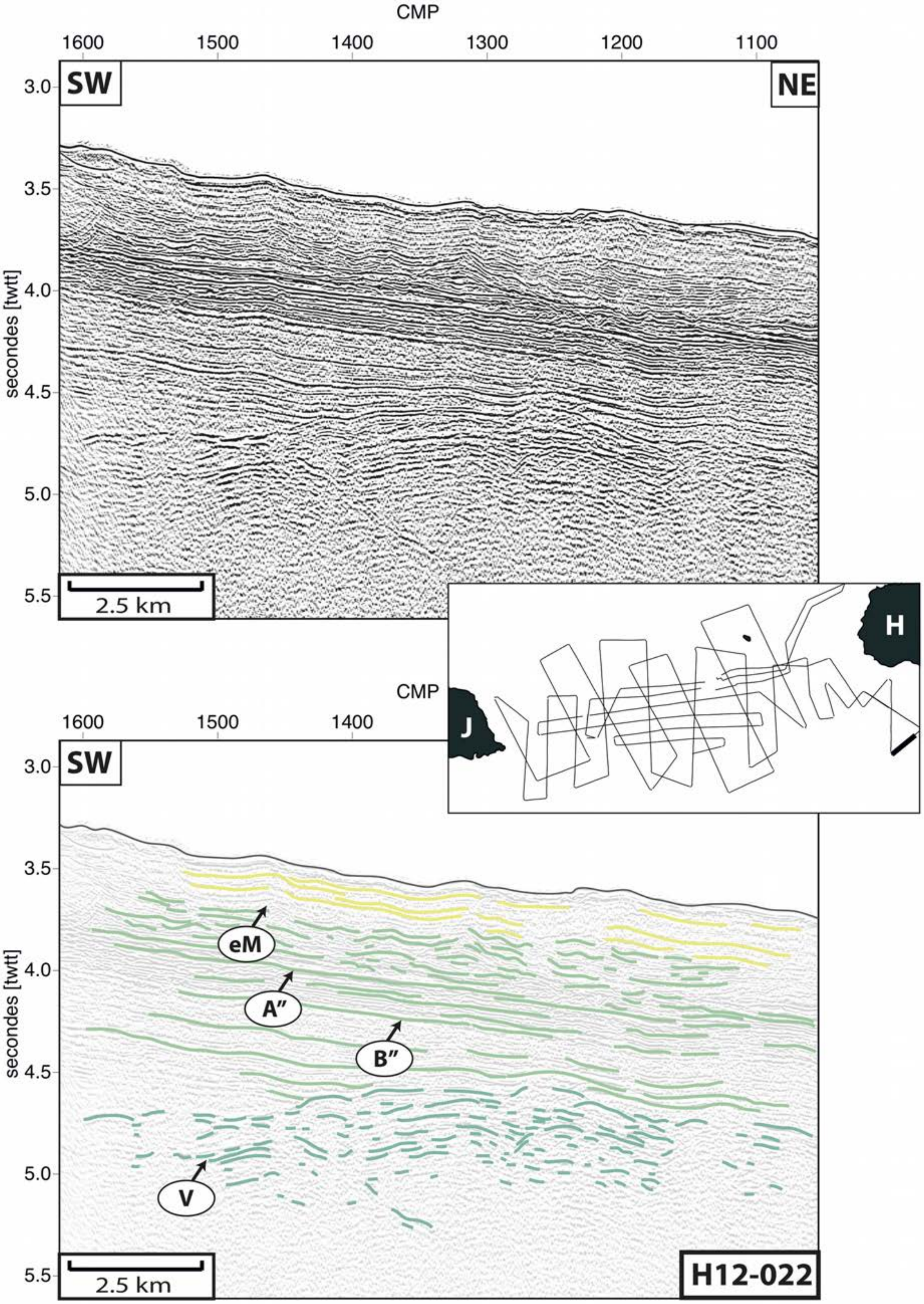

CMP
1600
1500
1400
1300
1200
1100
SW
NE
3.0
3.5
4.0
4.5
5.0
5.5
secondes [twtt]
2.5 km
H
J
eM
A''
B''
V
H12-022

Figure 16: Detail of seismic profile H12-022 (upper panel) and a possible interpretation (lower panel). See inset and Fig. 5 for location.

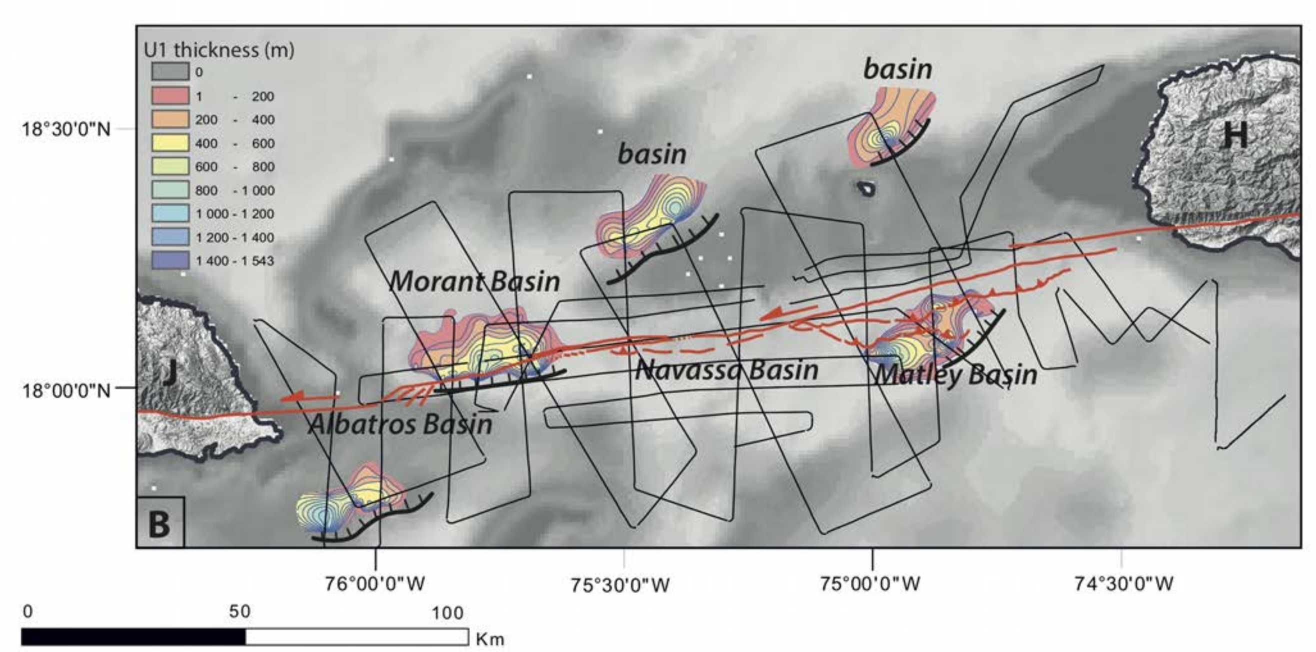


Figure 17: Isopach map of the U1 unit (syn-rift). The color scale indicates the depths in meters that are interpolated from the dense seismic coverage. Thicknesses are calculated with a velocity of 1500 m/s for the water layer and 2200 m/s for the interval U4-U2. The contour interval is 100 m. The normal faults identified in the seismic profiles are indicated in black, and the present-day trace of the EPGFZ is indicated in red. The thin lines represent the tracklines of the seismic profiles. J: Jamaica; H: Hispaniola. The background is the shaded bathymetry where no U1 unit is identified.

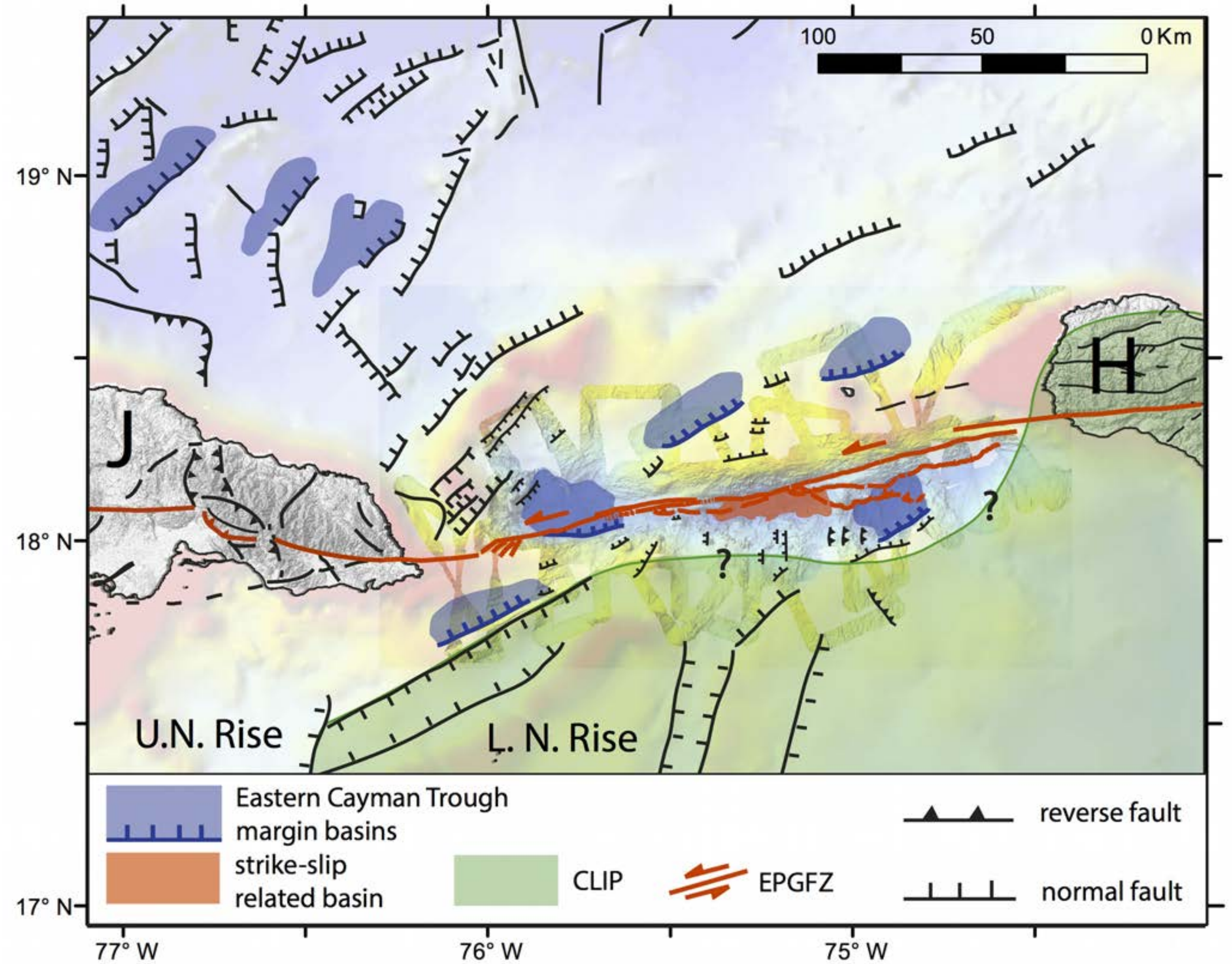


Figure 18: Structural sketch map of the Jamaica Passage showing our interpretation. J: Jamaica; H: Hispaniola. U. N. Rise: Upper Nicaraguan Rise, L. N. Rise: Lower Nicaraguan Rise. EPGFZ: Enriquillo-Plantain-Garden Fault Zone, CLIP: Caribbean Large Igneous Province.